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COMPARISON OF RADON AND THORON DAUGHTER BEHAVIOUR IN TWO UNDERGROUND URANIUM MINE ENVIRONMENTS

by

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SUMMARY

Measurements were made of aerosol concentration and size distribution in 5 locations downstream of working areas in two Canadian uranium mines which use track and trackless mining methods.

In the track mining area the aerosol concentration ranged from $3x10^4$ to $7x10^4/cm^3$, averaging $5x10^4/cm^3$. The count median diameter of the aerosol averaged 55 nm.

In the trackless mining area, aerosol concentrations ranged from $8x10^4$ to $30x10^4/cm^3$, averaging $14x10^4/cm^3$. The highest values were associated with the passage of diesel equipment. The count median diameter of the aerosol varied from 32 to 94 nm, with the smaller sizes associated with the presence of diesel exhaust.

The activity median diameter was measured for radon and thoron daughters in each environment. In the track mine the diameter of ^{218}Po, ^{214}Pb, ^{214}Bi averaged 54, 50, 54 nm respectively, and of ^{212}Pb averaged 70 nm.

In the trackless mine, these diameters were 73, 70, 85 and 100 nm respectively. The activity median diameter in terms of radon Total Potential Alpha Energy was found to be 89 nm.

Measurements of unattached fraction of radon and thoron daughters found that almost all daughters were attached to the aerosol.

The activity median diameter of the thoron daughter ^{212}Pb, was consistently larger than that of the radon daughters.

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Résumé

On a mesuré, dans deux mines d'uranium canadiennes, les concentrations en noyaux de condensation en aval de 5 chantiers ou groupes de chantiers en activité. Ces mesures recouvrent des situations de mines conventionnelles (minerai transporté par trains électriques) et des situations de mines non-conventionnelles (minerai transporté par véhicules diesels).

Dans les zones à transport conventionnel, la concentration des noyaux de condensation varie de 3.10^4 à 7.10^4 particules par cm^3, avec une concentration moyenne de 5.10^4 cm^{-3}. Le diamètre médian en nombre de l'aérosol est en moyenne de 55 nm.

Dans les zones à transport diesel, la concentration des noyaux de condensation varie de 8.10^4 à 30.10^4 cm^{-3}, avec une concentration en moyenne de 14.10^4 cm^{-3}. Les concentrations les plus hautes coïncident avec le passage d'engins diesels. Le diamètre médian en nombre de l'aérosol varie de 32 à 94 nm, les diamètres inférieurs correspondant à la présence de fumées d'échappement. Le diamètre médian en activité de l'aérosol a été mesuré à chaque endroit pour les produits de filiation du Radon et du Thoron. Dans les lieux à transports conventionnels, les diamètres de ^{218}Po, ^{214}Pb, ^{214}Bi sont en moyenne, respectivement 54, 50, 54 nm et 70 nm pour ^{212}Pb.

Dans les lieux à transports diesels, ces diamètres sont respectivement 73, 70, 85 et 100 nm. Le diamètre médian en activité lié à l'énergie potentielle alpha totale est 89 nm.

Des mesures de la fraction libre ont montré que les produits de filiation du Radon et de Thoron sont attachés dans leur presque totalité, à l'aérosol porteuse.

Le diamètre médian en activité de ^{212}Pb a constamment été trouvé plus grand que celui des produits de filiation de Radon.

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1. INTRODUCTION

This report has been prepared by DSMA ATCON LTD. (DSMA) in collaboration with Chemical Engineering Research Consultants Limited (CERCL) for the Atomic Energy Control Board (AECB) under DSS Contract OSQ84-00028, File No. 14SQ.87055-3-4110, entitled "Study of Thoron Daughters In An Underground Mine Environment Including Literature Review, Measurement of Carrier Aerosols and Area Monitoring". The mining companies provided access to their mines and allowed underground measurements to be taken. The Ontario Ministry of Labour and the AECB provided a good portion of the instrumentation used. All of this assistance is gratefully acknowledged.

The Phase I Literature Review and Assessment on "Thoron Daughters in an Underground Mine Environment" (DSMA Report No. 1381/1309) came to the conclusion that there were good theoretical and experimental reasons to believe that the attachment rate of the long lived thoron daughter ^{212}Pb (ThB) to the aerosol present in mines might be lower than that of the radon daughters. An underground experimental study was suggested to compare the behaviour of radon and thoron daughters to see if there was any significant difference between them in the mining environment.

This report presents the results of simultaneous measurements on radon and thoron progeny in two uranium mines. The respective decay schemes are shown in Tables 1a and 1b. Measurements were made of the unattached fraction of ^{212}Pb atoms, and count and activity size distributions of the carrier aerosols for the attached ^{212}Pb, and the thoron Working Level. Simultaneous measurements were also made of the unattached fractions, the activity size distributions, and the Working Levels of ^{218}Po, ^{214}Pb, ^{214}Bi. To investigate as wide a range of conditions as possible, measurements were made in two different mine environments. The first used tracked mining equipment, the second used diesel powered trackless equipment. The measurement techniques which were used, the data obtained, and a discussion of the results are presented herein.

The total time available for the mine measurements was 10 working days (two weeks), including orientation and set-up time. The time was divided evenly between the track and trackless test areas of the two mines.

2. MEASUREMENT TECHNIQUES

2.1 Unattached Fractions

Measurements of the unattached fractions of radon and thoron progeny were carried out using the wire screen method (Ge72). In this method, air is sampled simultaneously through two open face filter holders placed side by side, one containing the reference filter and the other containing a filter preceded by a 60 mesh wire screen. The wire screen is separated from the filter by an O-ring to keep the atoms of radon and thoron progenies deposited on the filter from reaching the wire screen by recoil. The wire screen efficiency for collecting the unattached atoms of radon and thoron progeny has experimentally been found to be 77% at a linear air velocity of 11.5 cm/s (Ge72). The efficiency of the wire screen can be calculated theoretically from Thomas and Hinchcliffe's equation (Th72):

$$E = 1 - (0.82\, e^{-0.333h} + 0.18\, e^{-16.7h}) \qquad (1)$$

where:

- h = 100 $M^2 d\, D/V$
- E = collection efficiency
- M = mesh size (mesh/cm)
- d = wire diameter (cm)
- D = diffusion coefficient of the atom under investigation (cm^2/s)
- V = linear air velocity (cm/s)

However, the diffusion coefficients of radon and thoron progeny are not accurately known and can vary significantly with ventilation rate (Ko76), charge state (Bi71), relative humidity (Ra79) and the nature of the gaseous environment (Bu81).

In order to understand the effect of this uncertainty on the exact value of the diffusion coefficient, theoretically calculated efficiencies for the wire screen used for this work are presented in Figure 1 as a function of diffusion coefficient. Figure 2 gives these efficiencies as a function of face velocity for the commonly assumed value of 0.054 cm^2/s for the diffusion coefficient of unattached ^{218}Po.

Since the specifications of the wire screen used for this work (60 mesh/inch, 0.007 inch or 0.018 cm wire diameter) are identical to those of the wire screen used by George (Ge72), his experimental efficiency value of 77% at 11.5 cm/s air velocity was used in equation (1) in order to find the corresponding value of the product Vh. This value was later used to calculate the collection efficiency corresponding to the measured air velocity in each case. George's efficiency arises from a particular value of the diffusion coefficient for his particular experimental conditions; this value and conditions and, therefore, his efficiency are not necessarily the

same as for the mine measurements conducted in this work. Any difference in conditions would result in an error in the calculated value of the unattached fraction.

The reference filter and the backup filter for the wire screen were counted in pre-calibrated Trimet ZnS alpha counters (Trimet Instruments Ltd. Model 372A) according to a pre-determined counting schedule. The detailed schedules followed for these measurements are given in Appendix A.

The unattached fraction was calculated from the differences in activities counted on the two filters and the appropriate wire screen efficiency. In three instances the unattached fraction was obtained by measuring the wire screens directly.

The sampling and counting schedule was determined by a mathematical procedure similar to that used by Busigin and Phillips (Bu80) for 3-count radon progeny determination and by Khan, Busigin and Phillips (Kh82) for 5-count radon and thoron progeny determination. A ten minute sampling period was adopted for mixtures of radon and thoron progeny (Kh82). A counting schedule was determined for four counting intervals for measurement of ^{218}Po, ^{214}Pb, ^{214}Bi and ^{212}Pb. Fluctuations in flow rate and concentration of individual species were each taken as 5%. For development of the counting scheme, the unattached counts of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi were taken to be 5% of typical levels (100, 60, 40, 2, and 1 pCi/L) found in uranium mines. The most suitable counting intervals were found to be 2-5, 9-25, 40-70 and 360-460 minutes after sampling. Within the allowed underground working period of about 5.5 hours, two samples per day could be obtained using this counting scheme. One more sample could be obtained by modifying the scheme a little in such a way that the uncertainties associated with the measurement were not affected appreciably. The counting scheme appropriate for this extra sample was determined to be 2-5, 9-25, 30-60 360-460 minutes after sampling. Only the third counting interval was shifted by ten minutes. The relative uncertainties in concentration for the two counting schemes are compared in Table 2. The calculation of these is presented in Section 3.

Equations for determining the concentrations of radon and thoron progeny from the counts obtained in the four counting intervals are given below. I(1), I(2), I(3), I(4) represent the counts obtained in the first, second, third and fourth counting intervals respectively. C(1), C(2), C(3) and C(4) denote the concentrations of ^{218}Po, ^{214}Pb, ^{214}Bi and ^{212}Pb, (uncorrected for collection efficiency) respectively. V is the pump flow rate in L/min and n is the efficiency of the counter.

For the counting scheme of 2-5, 9-25, 40-70, 360-460, the following apply: (Equation 2)

$$VnC(1) = 0.095346\ I(1) - 0.036333\ I(2) + 0.015622\ I(3) - 0.001732\ I(4)$$

$$VnC(2) = -0.010716\ I(1) + 0.000852\ I(2) + 0.004594\ I(3) - 0.000905\ I(4)$$

$$VnC(3) = -0.001851\ I(1) + 0.00935\ I(2) - 0.005512\ I(3) + 0.000696\ I(4)$$

$$VnC(4) = -0.0000002I(1) + 0.0000006I(2) - 0.0000099I(3) + 0.00065\ I(4)$$

For the counting scheme of 2-5, 9-25, 30-60, 360-460, the following apply: (Equation 3)

$$VnC(1) = 0.097002\ I(1) - 0.040587\ I(2) + 0.016187\ I(3) - 0.001254\ I(4)$$

$$VnC(2) = -0.010229\ I(1) - 0.000398\ I(2) + 0.00476\ I(3) - 0.000764\ I(4)$$

$$VnC(3) = -0.002435\ I(1) + 0.010851\ I(2) - 0.005711\ I(3) + 0.000527\ I(4)$$

$$VnC(4) = -0.0000003I(1) + 0.0000008\ I(2) - 0.000001\ I(3) + 0.00065\ I(4)$$

The concentrations were calculated for both the reference filter and the back-up filter for the wire screen using the appropriate set of equations. The unattached fraction, f_u, was then calculated as:

$$f_u = \frac{C_u}{C_{ref}} = \frac{C_{ref} - C_{bf}}{EC_{ref}} \qquad (4)$$

where:

C_u = concentration of the unattached species (pCi/L)

C_{ref} = concentration of the species collected on the reference filter (pCi/L)

C_{bf} = concentration collected on the back-up filter behind the wire screen (pCi/L)

E = efficiency of the wire screen for collecting the unattached species

The measurement schedule for unattached fractions was varied for the last two days of measurement because of the high levels of uncertainty associated with measurement of the smaller unattached fractions in the high aerosol environment of the trackless mine compared to that found in the track mine the previous week. Measurement of individual radon decay products was therefore abandoned for the last two days, and radon Working Levels were measured instead. In addition, in order to obtain more samples per day, the sampling period was reduced to 5 minutes and counting was carried out 2-7 minutes after sampling. This counting scheme was based on a rapid Working Level determination.

The radon Working Level was calculated for a 5 minute sample and 5 minute count 2-7 minutes after sampling using the following equation:

$$RnWL = \frac{I\ (2\text{-}7)}{5 \times 5 \times 235\ nV} \qquad (5)$$

where:

I(2-7) = counts obtained in 2-7 minutes interval after sampling

V = pump flow rate (L/min)

n = counting efficiency

During these 2 days, sampling for unattached thoron progeny was carried out over 15 minutes and the filters were counted at 330-360 minutes after sampling. The concentration of ^{212}Pb was calculated for a 15 minute sample and 30 minute count from:

$$C(^{212}Pb) = \frac{I\ (330\text{-}360)}{2.22xVx15x\ \exp\ (-\lambda(^{212}Pb)x345)xnx30} \qquad (6)$$

$$= \frac{I\ (330\text{-}360)}{1455.1\ Vn}$$

where: $\lambda(^{212}Pb)$ = disintegration constant of ^{212}Pb (min^{-1})

The thoron Working Level was calculated for a 15 minute sample and 30 minute count 330-360 minutes after sampling as follows:

$$TnWL = \frac{I(330-360)}{15 \times 30 \times 13\ nV} \qquad (7)$$

For the first sample of the last 2 days, however, thoron progeny activity was counted at 270-300 minutes after sampling in order to allow counting within the underground working time. Equation (7) was also used for calculating the TnWL in this case with the activity I(330-360) replaced by I(270-300). The concentration of ^{212}Pb is given in this case by:

$$C(^{212}Pb) = \frac{I\ (270-300)}{732.3\ Vn} \qquad (8)$$

The uncertainties associated with radon and thoron Working Level determinations by those methods were 6.8% and 9% respectively. These are discussed more fully in Section 3.

The unattached fractions were calculated from equation (4).

2.2 Aerosol Size Distributions

The decay products of radon and thoron eventually become attached to the surrounding aerosols. The total number size distribution of the aerosol and the activity size distribution of the aerosol to which radioactive atoms are attached (activity size distribution) will not in general be identical. In order to understand the behaviour of radon and thoron progeny in an aerosol environment, both aerosol and activity size distributions must be determined separately. An explanation of some commonly used terms is provided in Appendix D.

The aerosol size distribution in mines and the atmosphere can be adequately represented by a lognormal size distribution (Da74) where:

$$n(d) = \frac{1}{\sqrt{2\pi}\ \ln \sigma_g} \exp\left(-\frac{1}{2}\left[\frac{\ln\ (d/\bar{d})}{\ln\ \sigma_g}\right]^2\right) \qquad (9)$$

where:

$n(d)$ = size distribution function

$\bar{d}$ = count median diameter of the distribution

σ_g = geometric standard deviation of the distribution

d = particle diameter.

The count median diameter $\bar{d}$ and the geometric standard deviation can be determined via equation (9) and experimental data obtained from diffusion batteries (Bu80a). The relative penetration of aerosols through different sizes of diffusion batteries at specified flow rates allows the aerosol size distribution to be calculated.

Three diffusion batteries were used in conjunction with a portable (Environment One) condensation nuclei counter and a flow-regulated Dupont pump (Model P-4000). This instrument has a cut-off diameter of 2.5 nm. Air was first drawn through the sample port of the condensation nuclei counter by the pump to record the total aerosol concentration. The sample port was then connected to the three diffusion batteries one by one and the number of aerosol particles penetrating each battery obtained. The penetrations g_3, g_4 and g_5 through the diffusion batteries (nos. 3, 4 and 5) were then calculated from the ratio of the number of aerosols registered with and without a battery. An optimal fit of the Kth approximation of the size distribution $n^K(d)$ to the actual distribution $n(d)$ was then obtained using diffusion battery data. The experimental diffusion battery penetration, g_j, is related to the theoretically calculated penetration probability, $P_j(d)$, of a particle of size d by:

$$g_j = \int_0^\infty P_j(d)\ n(d)\ d(d) \qquad (10)$$

where $n(d)$ is the required aerosol size distribution.

The optimization calculation is aimed at minimizing the difference between g_j as given by equation (10) and the approximation g_j^K where:

$$g_j^K = \int_0^\infty P_j(d)\ n^K(d)\ d(d)$$

The penetration probability of a particle passing through the diffusion battery is given by:

$$P = \sum_{i=1}^{\infty} a_i \, e^{-b_i u} \qquad (11)$$

where:

u = 2 WLD/FH for a rectangular plate diffusion battery

W = width of each rectangular plate (cm)

L = length of each rectangular plate (cm)

D = diffusion coefficient of the particle (cm^2/s)

F = volume flow rate through a single channel in the diffusion battery (cm^3/s)

2H = spacing between two plates (cm) ($2H << W$)

The penetration constants a_i and b_i for parallel plate diffusion batteries are:

$a_1 = 0.91035$, $a_2 = 0.5314$, $a_3 = 0.01529$, $a_4 = 0.0068$

$b_1 = 1.88517$, $b_2 = 21.4317$, $b_3 = 62.3166$, $b_4 = 124.5$

The dimensions of the diffusion batteries are given in Table 3.

At a nominal sampling rate of 3 L/min, diffusion battery (D.B.) No. 3 would remove 50% of the 0.03 um particles, D.B. no. 4 would remove 50% of the 0.08 um particles and D.B. no. 5 would remove 50% of the 0.2 um particles. Penetration vs diffusion coefficient curves for the three diffusion batteries at various flowrates (Figure 3), together with the particle diameter vs diffusion coefficient relationship (Fr77) (Figure 4) allow the penetration to be calculated for various size particles. In the calculations, the actual flow rate at the time of measurement in each diffusion battery is used.

For each diffusion battery, j, the count median diameter, $\bar{d}$, and the geometric standard deviation, σ_g , were calculated by using the experimental diffusion battery penetration value, g_j, as input for a computer program based on the optimization procedure described earlier.

The volume median diameter dv can also be described by a lognormal distribution with the same geometric standard deviation as the original size distribution and is given by:

$$\ln d_v = \ln d + 3(\ln \sigma_g)^2 \qquad (12)$$

2.3 Activity Size Distribution

For the activity size distribution determination, the concentration of the radioactive species of interest is used instead of the aerosol concentration. The experimental method consists of drawing air through 25-mm-diameter millipore Type AA filters placed in magnetic filter holders at the air exit ends of the diffusion batteries. These filters have a pore size of 0.8 um. An open face filter holder with a similar filter was used as a reference. Air was drawn simultaneously through the reference filter and the three diffusion batteries for ten minutes. The filters were then counted in Trimets according to a preset counting schedule in order to estimate ^{218}Po, ^{214}Pb, ^{214}Bi and ^{212}Pb. The fluctuations in flow rate and concentrations during sampling were taken as 5% each. Two samples per day could be obtained using this schedule of 10 minutes sampling and subsequent counting at 2-4, 9-12, 85-95 and 240-250 minutes after sampling. An extra count for the reference filter was obtained at 650-750 minutes for each sample in order to determine the concentration of ^{212}Bi. The detailed schedules for sampling and counting are given in Appendix A.

The following equations for diffusion battery measurements were used to calculate the concentrations C(1), C(2), C(3) and C(4) for ^{218}Po, ^{214}Pb, ^{214}Bi and ^{212}Pb, respectively. (Equation 13)

$$nVC(1) = 0.146577\ I(1) - 0.135175\ I(2) + 0.039193\ I(3) - 0.02596\ I(4)$$

$$nVC(2) = -0.0167797\ I(1) + 0.009946\ I(2) + 0.022673\ I(3) - 0.017961\ I(4)$$

$$nVC(3) = -0.0072511\ I(1) + 0.035622\ I(2) - 0.017533\ I(3) + 0.012187\ I(4)$$

$$nVC(4) = -0.00001194I(1) + 0.0000433I(2) - 0.0001868I(3) + 0.005955\ I(4)$$

The concentration of ^{212}Bi was obtained from the following equation: (Equation 14)

$$nVC(5) = -0.00019\ I(1) + 0.00069\ I(2) - 0.00297\ I(3) + 0.09485\ I(4) - 0.01405\ I(5)$$

In the above equations, I(j) is the count obtained in the jth counting interval, and n and V are the counting efficiency and the sampling flow rate (L/min) respectively.

For the last two days of measurements, the sampling and counting schedules were varied in order to increase the number of samples obtained per day from two each to four each, for both the radon and thoron progeny. The activity size distribution for radon progeny could only be obtained in terms of the radon progeny Working Level, however. The scheme consisted of 5 minute sampling followed by 2-7 minute counting for radon progeny and 15 minutes sampling followed by 330-345 minute counting for thoron progeny. The schedule for sampling and counting based on this scheme is provided in Appendix A.

The radon progeny Working Levels were calculated using equation (6). The thoron progeny Working Level were calculated as:

$$TnWL = \frac{I\ (330\text{-}345)}{15 \times 15 \times 13 \quad V} \qquad (15)$$

However, the first sample of the day was counted at 270-285 minutes after sampling in order to allow counting to be completed in the underground working period. Equation (15) was used to calculate the thoron progeny Working Level in this case, with I(330-345) replaced by I(270-285).

The concentration of ^{212}Pb was calculated from:

$$C(^{212}Pb) = \frac{I\ (330\text{-}345)}{2.22xVx15x15x\ \exp(-\ (^{212}Pb)x337.5)xn} \qquad (16)$$

$$= \frac{I(330\text{-}345)}{345.78\ Vn}$$

For the first sample of the day, this concentration was given by:

$$C(^{212}Pb) = \frac{I(270\text{-}285)}{369.14\ Vn} \qquad (17)$$

The activity size distributions were determined from the calculated concentration penetration values for the diffusion batteries using the method outlined in the previous section.

2.4 Working Level Measurement

Two simultaneous samples were taken twice daily to determine the Working Levels of radon and thoron progeny, except on the last two days. On the last two days, each measurement was aimed only at evaluating the Working Levels, and so additional Working Level measurements were not required.

The method for determining Working Level consisted of sampling air for ten minutes through an open face filter holder containing a 0.8 um pore size filter. The filter was then counted at 2-7 and 340- 350 minutes after sampling in accordance with a two-count scheme for determining radon and thoron progeny Working Level (Kh85). The following equations were used for the calculations:

$$RnWL = \frac{I(2\text{-}7)}{10 \times 5 \times 235 \times Vn} = \frac{I(2\text{-}7)}{11750\ Vn} \qquad (18)$$

$$TnWL = \frac{I(340\text{-}350)}{10 \times 10 \times 13 \times Vn} = \frac{I(340\text{-}350)}{1300\ Vn} \qquad (19)$$

The I's represent the counts obtained in the counting interval shown parenthetically in minutes, V is the pump flowrate, and n is the counter efficiency.

2.5 Ventilation Rate

The ventilation period at each sample location was measured by releasing SF_6 tracer gas upstream of the sampling location. Air samples were collected at minute intervals in test-tubes which were then sealed. The relative SF_6 concentrations in these tubes were measured by gas chromotography, and plotted on semi-log graph paper against time. The time required per airchange, or ventilation period, was obtained from the time required for the relative SF_6 concentration to fall to 1/e of its maximum. The ventilation rate in ft^3/min was calculated by dividing the estimated volume of stope or drift between SF_6 release point and sample point by the time per airchange.

Air velocities at the sampling location were measured at the same time as the SF_6 ventilation tests were taken so that observed changes in air velocity could be transformed into estimates of changes in ventilation rate.

3. UNCERTAINTIES IN THE MEASUREMENTS

In order to judge the validity of the information obtained from a set of measurements, it is necessary to evaluate the uncertainties associated with the measurements. In unstable and complex atmospheres such as in working mines, uncertainties arising from uncontrolled variations in the atmosphere become important. The various sources of uncertainty in the measurement of unattached fractions, aerosol and activity size distributions and the Working Levels are discussed here, together with measures taken to reduce sources of error wherever possible. Also discussed is the extent to which the final results are effected by the overall uncertainties.

3.1 Flow Rate Fluctuations

A general source of error in all measurements involving pumps stems from the uncertainty in the volume of air sampled. This can arise from errors in estimating the flow rate, as well as from the fluctuations in the flow rate during a measurement. The pumps used for these mine measurements (Dupont P-4000) are flow feedback controlled and demonstrate excellent constancy of flow over periods of 5-15 minutes. Since the measurement periods used were 5-15 minutes, the flow rate did not vary over the duration of each measurement.

For the first two days, the pumps were calibrated against a pre-calibrated rotometer the night before. However, it was discovered on the second day of measurements that the flow rate fell during the day as the batteries became discharged. Part of the first day's data had to be rejected due to this unsuspected drop in flow rate. From then onwards (January 31st), the flow rate was checked during each measurement. A rotameter was connected to the exhaust of the pump and the flow rate was recorded during the sampling period.

In the laboratory, the flow rate was accurately measured by a soap film flow meter connected to the outlet of a pump drawing air through a 25 mm open face filter holder containing a filter. This agreed within ±2% with the flow rate recorded by the rotameter at the pump oulet. Reserving a margin of ±3% error for reading the flow rate off the rotameter scale in underground conditions, the error in flow rate for each measurement is estimated as certainly less than ± 5%.

3.2 Radionuclide Concentration Uncertainties

As a result of instabilities in the mine atmosphere, caused by ventilation changes and work operations, the concentrations of radioactive species may change appreciably during the sample period. The uncertainty due to this variability in concentration must be considered. The uncertainty calculations for the reported mine measurements were based on a 5% fluctuation in concentration of each radionuclide of interst during the period of sampling. The method of calculating the individual uncertainties is as follows.

The equations for the expected number of atoms, $\bar{N}_i$, of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi at the end of sampling are:

$$\bar{N}_i = \sum_{j=1}^{5} a_{ij} \bar{V} \bar{C}_j \qquad (20)$$

where $\bar{V}$ is the average sampling flowrate and $\bar{C}_j$ is the concentration of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Po and ^{212}Bi respectively for j = 1, 2, 3, 4, 5. In the equations for $\bar{N}_i$, a_{ij} is the coefficient of $\bar{V}\bar{C}_j$ with $a_{ij} = 0$ for j>i and for i = 4, 5 when j = 1, 2, 3. The detailed equations are reported elsewhere (Kh82).

Similarly, the expected number of alpha disintegrations in four independent counting intervals $I_1(t_1-t_2)$, $I_2(t_3-t_4)$, $I_3(t_5-t_6)$ and $I_4(t_7-t_8)$, where t_x is the time in minutes after sampling, can be expressed as:

$$\bar{I}_k = \sum_{i=1}^{5} b_{ki} \bar{N}_i \qquad (21)$$

where k = 1, 2, 3, 4.

This set of equations can be re-expressed as:

$$\bar{N}_i = \sum_{k=1}^{4} d_{ik} \bar{I}_k \qquad (22)$$

for i = 1, 2, 3, 4 for four counting intervals.

From equations (20) and (22), the airborne concentrations $\bar{C}_j$ can be expressed as:

$$\bar{V} \bar{C}_j = \sum_{k=1}^{4} e_{jk} \bar{I}_k \qquad (23)$$

where j = 1, 2, 3, 4.

The standard deviations of the number of atoms, $\bar{N}_i$, present on the filter at the end of sampling were estimated by standard statistical procedures:

$$(\Delta N_1)^2 = a_{11}^2 \left[(\bar{V} \Delta C_1)^2 + (\bar{C}_1 \Delta V)^2 \right] + \bar{V} \bar{C}_1 T - \bar{N}_1 \qquad (24)$$

$$(\Delta N_2)^2 = a_{21}^2 \left[(\bar{V} \Delta C_1)^2 + (\bar{C}_1 \Delta V)^2 \right] + a_{22}^2 \left[(\bar{V} \Delta C_2)^2 + (C_2 \Delta V)^2 \right] + 2 \bar{V} \bar{C}_1 T + \bar{V} \bar{C}_2 T - 2 \bar{N}_1 - \bar{N}_2 \qquad (25)$$

$$(\Delta N_3)^2 = a_{31}^2 \left[(\bar{V}\,\Delta C_1)^2 + (\bar{C}_1\,\Delta V)^2\right] + a_{32}^2 \left[(\bar{V}\,\Delta C_2)^2 + (C_2\,\Delta V)^2\right] + a_{33}^2 \left[(\bar{V}\,\Delta C_3)^2 + (\bar{C}_3\,\Delta V)^2\right] + 2\,\bar{V}\,\bar{C}_1\,T + 2\,\bar{V}\,\bar{C}_2\,T + \bar{V}\,\bar{C}_3\,T - 2\bar{N}_1 - 2\bar{N}_2 - \bar{N}_3 \qquad (26)$$

$$(\Delta N_4)^2 = a_{44}^2 \left[(\bar{V}\,\Delta C_4)^2 + (\bar{C}_4\,\Delta V)^2\right] + \bar{V}\,\bar{C}_4\,T - \bar{N}_4 \qquad (27)$$

It was assumed in these calculations that the concentrations $\bar{C}_1$ to $\bar{C}_4$ and the flow rate $\bar{V}$ can be treated as independent random variables. The first terms (within brackets) in the above equations represent uncertainties due to fluctuations in flow and concentration while the last terms represent uncertainties due to the randomness of radioactive decay. T is the sampling time (in minutes) in the above equations.

The effect of counting statistics is given by $\sqrt{\bar{I}_k/E}$ where E is the counting efficiency of the alpha counter employed in the measurement.

The overall uncertainty in the measured activites, I_k, can therefore be expressed as:

$$(\Delta I_k)^2 = \sum_{i=1}^{4} (b_{ki}\ \Delta N_i)^2 + \frac{\bar{I}_k}{E} \qquad (28)$$

The standard deviations in the concentration measurements, S_j, can be determined from equation (23) as:

$$S_j^2 = \sum_{k=1}^{4} (e_{jk}\ \Delta I_k)^2/\bar{V}^2 \qquad (29)$$

The relative standard deviations RSD_j are then:

$$RSD_j = \frac{S_j}{C_j} \qquad (30)$$

In determining the sampling and counting schedules, the criterion used was to minimize the relative standard deviation for ^{218}Po (RSD_1), since the uncertainty for ^{218}Po is the largest for the four radionuclides of interest.

Under experimental conditions, many other constraints had to be satisfied. Four alpha counters, two experimentalists and an underground working period of 5.5 hours were the constraints used for determining the test schedules. For the diffusion battery measurements, simultaneous counting of four filters using four counters constrained each counting interval to be less than or equal to the sampling period.

Concentrations of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi were taken as 100, 60, 40, 2 and 1 per pCi/L, respectively, for diffusion battery measurement calculations and 5% of each concentration was assumed for selection of the unattached fraction calculation methods. The flow rate and counting efficiency values assumed were 3 L/min and 40% respectively. These assumptions were used for estimation of uncertainties and optimization of counting-time intervals.

The uncertainties obtained by this procedure are given in Table 4. The procedure was extended to include the measurement of concentrations of ^{212}Bi and the associated uncertainties for the reference filter used for diffusion battery measurement. The associated uncertainty was found to be too high to allow useful information to be obtained from this additional, twice daily measurement. The results for ^{212}Bi concentrations are, therefore, not included in the data evaluation.

On the last two days of measurement (Feb. 7 and Feb. 8), the sampling and counting schedules were changed to measure only radon and thoron progeny Working Levels. The details of these schedules are given in Section 2.

The uncertainties reported in Table 5 are based upon:

$$\left(\frac{\Delta RnWL}{RnWL}\right)^2 = \left(\frac{\Delta I_1}{I_1}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 \qquad (31)$$

and

$$\left(\frac{\Delta TnWL}{TnWL}\right)^2 = \left(\frac{\Delta I_2}{I_2}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 \qquad (32)$$

where I_1 and I_2 are the alpha disintegrations obtained in the appropriate counting intervals specified for determining radon and thoron progeny Working Levels, respectively. Uncertainties for two-count Working Level determination by grab sampling are also given in Table 5. The last column in this Table gives the accuracy of the WL as calculated by the one or two count methods relative to the actual RnWL(TnWL) for the concentrations 100, 60, 40, 2 and 1 pCi/L for ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi respectively.

It should be noted that there is no need to correct the radon working level for thoron progeny content, or vice versa. The four and five count methods result in concentrations estimates for the individual daughters of radon and thoron. The particular working levels are then calculated by appropriately combining only those daughter concentrations which are

respectively involved. In the one and two count methods, the counting times for calculation of RnWL or TnWL are respectively sufficiently prompt or sufficiently delayed after sampling that from practical considerations any cross-contribution is well within the uncertainty from counting statistics alone.

3.3 Size Distribution Measurement Errors

The method for size distribution determination, for both activity and aerosols, is outlined in Section 2. The optimal fit of the theoretically determined size distribution n(d) to the experimentally obtained size distribution $n^K(d)$ and therefore to the diffusion battery measurement data is obtained by minimizing a performance index, P.I., of the following form:

$$P.I. = \sum_{j=1}^{n} \left[g_j - \int_0^{\infty} P_j(d)\, n^K(d)\, d(d) \right]^2 \qquad (33)$$

The parameters g_j and $P_j(d)$ have been defined in Section 2. The constraints used to ensure a reasonable solution were:

$$0 < d^{(k)} < 1\ \mu m \qquad (34)$$

and

$$1 < \sigma^{(k)} < 10 \qquad (35)$$

The value of the performance index P.I. (see Appendix C) can be used to estimate the accuracy of the results. Generally a performance index of less than or equal to 0.02 indicates an excellent fit. It must be realized however, that in mine measurements the experimental data can be expected to reflect the instability of the atmosphere and could, therefore, be difficult to fit to a theoretically determined size distribution. Performance Indices as high as 0.1 or more have also been obtained in the reported measurements.

In the activity size distribution measurements the uncertainties associated with concentration measurements, discussed in the previous section, would be carried forward into the fitting of theoretical calculations to the experimental data, thereby resulting in higher performance indices than for aerosol number size distributions.

3.4 Unattached Fraction Measurement Errors

In addition to the errors mentioned in Sections 3.1 and 3.2, the measurement of unattached fractions presents a further challenge as a result of large errors associated with the measurement of small activities on the wire screen. Furthermore, the wire screen efficiency determined from the method outlined in Section 2 is not well known since the diffusion coefficients of radon and thoron progeny atoms are ill defined.

Direct determination of activity deposited on the wire screen is possible, however, the complex geometry of a wire screen and the irregular pattern of deposition of particles or atoms on it make estimation of its counting efficiency, allowing for self-absorption, somewhat difficult. This problem has been investigated with some success by George (Ge72) and Stranden (St82).

The unattached fraction can be calculated from measurement of progeny concentrations on the wire screen as:

$$f_u' = \frac{C_{ws}}{KE\ C_{ref}} \qquad (36)$$

where:

C_{ws} = concentration calculated from activity on the wire screen

C_{ref} = concentration calculated from activity on the reference filter

E = efficiency of capture of unattached progeny by the wire screen

K = the relative counting efficiency of the wire screen.

The standard deviation in unattached fraction by the wire-screen method can therefore be calculated from

$$\sigma_{f_u'} = f_u' \left[\left(\frac{\sigma_{C_{ws}}}{C_{ws}} \right)^2 + \left(\frac{\sigma_{C_{ref}}}{C_{ref}} \right)^2 + \left(\frac{\sigma_{KE}}{KE} \right)^2 \right]^{\frac{1}{2}} \qquad (37)$$

where the relative uncertainty in the product KE can be assumed as 10% (GE72, ST82). Typical relative uncertainties in progeny concentrations from filter measurements (ie. C_{ref}) are provided in Table 2 under the assumption of an unattached fraction of 0.05. Similar calculations could be performed to determine typical uncertainties in progeny concentrations on the wire screen, using equation 2 with typical counts and standard error propogation.

For example, the largest relative uncertainty is expected in the concentration of ^{218}Po(RaA) and is estimated as 37%. When this is incorporated in equation 37, the typical relative uncertainty in unattached fraction of ^{218}Po is estimated as 48%. Although this percentage error is large, it sets reasonably tight bounds to the assumed unattached fraction of 0.05. The experimental result can be expected at a 68% confidence level, to fall within the range of $0.026 < f_A < 0.074$. For the unattached fraction of other progeny (^{214}Pb, ^{214}Bi, and ^{212}Pb) one can expect the ranges to be

even tighter. Some attached activity can also be deposited on the wire screen, thereby constituting a further source of error. Van der Vooren, Busigin and Phillips (Va82) discussed all sources of error in unattached fraction measurements and concluded that measurements are probably not accurate to more than one significant figure.

An alternate method involves taking the difference between the reference filter activity and the activity deposited on the filter behind the screen. For small unattached fractions the raw counting statistics of the individual filters are greatly improved over those associated with the wire screen. However, since two similarly sized numbers are involved in the subtraction, the small resulting difference can have a large error. Other measurement errors in this case include uncertainties due to flow fluctuations, concentration fluctuations, and randomness of radioactive decay during sampling.

The unattached fraction by the difference method is defined in equation 4. Consequently the uncertainty in unattached fraction is given by:

$$\sigma_{f_u} = \left[\frac{1}{E^2}\left\{\left(\frac{1}{C_{ref}}\right)^2 \sigma_{C_{bf}}^2 + \left(\frac{C_{bf}}{C_{ref}^2}\right)^2 \sigma_{C_{ref}}^2\right\} + \frac{1}{E^2}\left(1 - \frac{C_{bf}}{C_{ref}}\right)^2 \left(\frac{\sigma_E}{E}\right)^2\right]^{\frac{1}{2}} \quad (38)$$

Since the relative uncertainty in E is approximately 0.05, and since C_{bf} is almost equal to C_{ref}, equation 38 can be reduced to

$$\sigma_{f_u} = \left[\frac{2\sigma_C^2}{E^2 C^2}\right]^{\frac{1}{2}} = \frac{\sqrt{2}}{E}\left(\frac{\sigma_C}{C}\right) \quad (39)$$

The uncertainty in the unattached fractions can therefore be estimated from data in Table 2 and the assumption that E = 0.72, from Figure 2 for a face velocity of 12 cm/s corresponding to a flow rate of 3 lpm. The resulting estimates are that $\sigma_{f_A} = 0.56$, $\sigma_{f_B} = 0.13$, $\sigma_{f_C} = 0.34$, and $\sigma_{f_T} = 0.10$. Therefore the probability distributions associated with the measurement of small unattached fractions by the difference method have a high relative dispersion.

4. MEASUREMENT LOCATIONS AND CONDITIONS

Measurements were made at two locations in the track mine and at three locations in the trackless mine.

4.1 Track Mining

Measurements were made in the exhaust airway of an active stope (#107012), on January 29, 30 and 31 (Site 1). On the 29th, drilling was carried out for a few short periods during the shift, and a small blast took place about 9:30 hrs. On the 30th, drilling was almost continuous throughout the shift and a small blast took place at 13:40 hrs. The ventilation airflow through the stope on these two days varied between 320 to 460 m^3/min (11,200 to 16,000 cfm) giving a ventilation period (residence time) in the stope of about 12 minutes as determined by SF_6 tests. On the 31st, drilling was carried out for most of the shift. The airflow through the stope was reduced to 210 to 360 m^3/min (7,360 to 12,800 cfm) during the shift by construction of a platform across an open boxhole, increasing the air residence time to 20 minutes.

On the 1st of February, the measurement location was moved to an area of higher WL (Site 2) in an exhaust drift (#904) supplied mainly with the exit air from an inactive stope (#1054). The ventilation airflow was 415 to 530 m^3/min (14,600 - 18,700 cfm), giving a ventilation period (residence time) in the stope of about 8 minutes.

4.2 Trackless Mining

Measurements were made in a main exhaust airway (#43951) (Site 3) which carried 6300 to 7900 m^3/min (224,000 to 280,000 cfm) of air on the 4th of February. This airway ventilated active workings, and was a main travelway. Equipment was set up out of vehicular traffic flow in a cut-out leading to an electrical substation. This location was not felt to be satisfactory on account of the traffic.

Another location was tried on the 5th of February (Site 4). This was a smaller exhaust drift (#45952), carrying 200 to 790 m^3/min (7,000 to 28,000 cfm) of air from active workings, and less traffic. The equipment was set up just out of the traffic flow outside an old lunch room. This location was not felt to be satisfactory because of the large flow variations and turbulence caused by an upstream ventilation fan supplying an underground garage, and the amount of traffic.

The final location was in a major exhaust airway (#45964) carrying a fairly constant 3000 m^3/min (106,000 cfm) (Site 5) from inactive workings. This was not a major travelway and vehicular traffic was rare. Measurements were made here on the 6th, 7th, 8th of February.

4.3 Relative Humidities

The surface air supplied to the mines is heated to a little above 0°C to prevent freezing in the downcast shafts, and large amounts of water are sprayed into the air, on road beds and on ore to limit the amount of quartz dusts generated. As a result, the air in the mine is cool (10°C), and relative humidities are high.

The relative humidities at each site were measured by a sling psychrometer, read to ± 0.1°C.

At Site 1, over three days of measurement, the dry bulb temperature ranged from 10.6 to 11.6°C, with RH from 76 to 88%.

At Site 2, over one day the dry bulb temperature ranged from 11.0 to 11.8°C, with RH from 65 to 68%.

At Site 3, the dry bulb temperature ranged from 13.2 to 14.0°C, with RH from 72 to 78%. The higher temperatures are the result of heat rejection into the atmosphere by the diesel engines.

At Site 4, dry bulb temperature was constant at 15°C, with RH of 81 to 86%.

At Site 5, over 3 days of measurement, the dry bulb temperature ranged from 12.2 to 13.2°C. RH ranged from 83 to 86% over the first two days, until the water, which had pooled around and partially submerged the fans located 300 m upstream of the sample location, had been drained mid-way through the second day. RH ranged from 76 to 78% on the last day after the water had been drained.

5. RESULTS

The results of experimental measurements are presented in tables and graphs in order to allow conclusions to be drawn about the unattached fractions of radon and thoron progeny, and their relationship, if any, to the size distribution of the surrounding aerosol, the aerosol concentration, temperature, relative humidity and the ventilation rate. Only the final calculated results are presented in this section; the experimental data are listed in Appendix B. Processed data for aerosol and activity size distributions and unattached fractions are presented in Appendix C.

The period January 29 - February 1 was spent in measurements inside a track mine. The February 4 - February 8 measurements were obtained in a trackless (diesel-operated) mine. A daily history during sampling of the average conditions of aerosol concentration, temperature, humidity, ventilation rate and the kinds of activities taking place in the measurement aera, are presented in Table 6. The Working Levels of radon and thoron progeny are shown in Table 7 as measured by separate grab samples and also as calculated from the measured concentrations of the individual progeny (^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi). Table 8 provides a summary of the unattached fractions and the aerosol and activity size distributions together with the time of the day of each measurement. The time of day needs to be noted if correlation between data sets in Tables 6, 7, and 8 are to be attempted.

The results are also plotted. For example, Figures 5-8 show the frequency distributions, for track and trackless mines combined, for RaA, RaB, RaC and ThB, respectively. Figures 9-17 show the activity size distributions of ^{218}Po, ^{214}Pb, ^{214}Bi and ^{212}Pb for both mines and the radon progeny Working Level distribution for the trackless mine. The aerosol concentration data are shown in Figures 18-25 for each measurement day. This set of figures is of particular importance since it illustrates the extreme variability of the mine atmoshphere. Figures 26-32 are plots of the aerosol size distributions as determined from the diffusion battery-condensation nuclei counter measurements. The frequency distributions of the count median diameters of the aerosol size distributions are shown in Figure 33 for each mine separately.

In addition to the aforementioned great variability in mine atmosphere, ventilation rates are also variable, and ongoing activities close to the measurement area can result in uncontrolled changes in the radon/thoron progeny activities, during a measurement, which are even larger than those used to provide the uncertainty estimates of Table 4. Mine measurements can therefore be subject to a wide scatter and it is common to find that certain data are not physically meaningful. For example, Tables 7a and 7b contain data sets which are ignored because they predict either a ^{214}Pb/^{218}Po concentration ratio or a ^{214}Bi/^{218}Po concentration ratio of greater than unity, a physically impossible situation.

5.1 Working Levels

Working Levels for radon and thoron progeny listed in Tables 7a and 7b have been computed from the concentrations of individual radionuclides as measured, and from a two-count measurement. Although the computation based on individual concentrations is believed to be more accurate, the two-count method, nonetheless, yields Working Level values in very good agreement. The following Working Level results are typical of the time and location of sampling and cannot be generalized.

5.1.1 Track Mining Area

The thoron progeny Working Level was slightly higher than the radon progeny Working Level throughout the first three days of measurements. The Working Level range was 0.08-0.21 for radon progeny and 0.12-0.22 for thoron progeny. On the fourth day of measurements, the location was changed. Working Levels were higher in this area, in the range 0.39-0.51 for radon progeny and 0.36-0.44 for thoron progeny. In this area, the thoron progeny Working Levels were found to be either equal to or slightly less than the radon progeny Working Levels.

5.1.2 Trackless Mining Area

The radon progeny Working Levels were in the range 0.26-0.39, as seen in Table 7b and Table 7c. The thoron Working Levels were in the range 0.19-0.30 and were always lower than the radon Working Levels in each measurement.

5.2 Aerosol Concentrations

5.2.1 Track Mining

The aerosol concentration in the active stope (Site 1) is plotted over the shift in Figures 18, and 19. The concentration averaged $5x10^4/cm^3$, ranging from $3x10^4$ - $7x10^4/cm^3$. Drilling produced concentration increases in the order of $1x10^4/cm^3$ from a baseline level in the region of $3x10^4$ to $5x10^4/cm^3$. The aerosol concentration in the inactive stope (Site 2) is plotted over the shift in Figure 20. The aerosol concentration was almost constant at $7x10^4/cm^3$. The difference between these two locations is thought to be due to diesel equipment operating in the area upstream of the inactive stope.

5.2.2 Trackless Mining

The aerosol concentration in each of the areas is plotted over the shift in Figures 21, 22, 23, 24, and 25, and averages $12x10^4/cm^3$ in all locations, but ranged from a low of $8x10^4/cm^3$ to over $30x10^4/cm^3$ (full scale on the counter) when a vehicle passed by. Measurements made during such transient conditions present problems in interpretation because the attachment rate of radon and thoron progeny atoms is directly proportional to the aerosol area. Coagulation at these high aerosol concentrations rapidly changes the

aerosol area and changes the size distribution, both of which affect the attachment rate. The rapidity of the concentration changes, and the unpredictable nature of the vehicular traffic means that size measurements must be carried out simultaneously. The three diffusion batteries and the reference were placed side by side to avoid such errors due to transient conditions.

5.3 Size Distributions

The count and activity size distributions calculated from the diffusion battery data are given in Table 8. The average value median diameters for each mine are shown in Table 10.

The histograms in Figure 33 present the aerosol size measurements and indicate that the count median diameter of particles in the track mine was in the range of 40-80 nm, while those in the trackless mine was in the range 30 -100 nm with relatively large scatter in data compared to the track mine.

5.3.1 Track Mine

The aerosol diameter was virtually constant on each day. The mean values were 51 and 64 nm in the active stope on the 30 and 31 January, and 48 nm in the inactive stope on 1 February. The geometric standard deviation of the aerosol averaged 2.0 over these 3 days.

The activity size distribution for each radioactive species was compared with the count size distribution by examining the ratio of these diameters. On average, the activity median diameter for radon daughters was equal to the count median diameter of the aerosol. The activity median diameter for ^{212}Pb was always larger than the count median diameter - on average 30% larger.

5.3.2 Trackless Mine

The aerosol diameter varied over the day, and from day to day. The largest value was 94 nm on the 4 February, and the smallest value was 32 nm on the 5th February. Smaller values of the carrier aerosol were associated with measurements made close to the passage of a vehicle, and presumably reflected the small size distribution of fresh exhaust aerosols. As the aerosol diameter was so variable with time, the activity median diameter could not be compared with it directly. At sites 3,4, and 5 on Feb. 4, 5, and 6 the range of median diameters was 66 to 84 nm for ^{218}Po, 53 to 91 nm for ^{214}Pb, 77 to 96 nm for ^{214}Bi, and 92 to 100 nm for ^{212}Pb. On February 7 and 8 activity size distributions were measured in terms of radon working level and ^{212}Pb. The working level median diameters ranged from 85 nm to 97 nm and for ^{212}Pb they ranged from 106 nm to 125 nm.

The activity size distributions of each radioactive species was compared. The diameter of ^{218}Po and ^{214}Pb were about 14% smaller than that of ^{214}Bi, and that of ^{212}Pb was always larger by about 22%.

5.4 Unattached Fraction

Most of the unattached fractions in this report were measured by the difference of filters method and are reported in Table 8. In the track mine, unattached fractions ranged from -0.06 to 0.84 for ^{218}Po, 0.08 to 0.35 for ^{214}Pb, -0.17 to 0.36 for ^{214}Bi, and 0.03 to 0.34 for ^{212}Pb. For the trackless mine, the unattached fractions were found to be in the range -0.02 to 0.54 for ^{218}Po, 0.03 to 0.25 for ^{214}Pb, -0.03 to 0.36 for ^{214}Bi and -0.02 to 0.29 for ^{212}Pb. Furthermore, the unattached fraction of radon progeny (mainly ^{214}Bi) measured by a Rolle count on the last two days of measurement in the trackless mine, ranged from 0.06 to 0.26, close to the value for ^{214}Pb measured at the same time.

Negative unattached fractions, although physically meaningless, have been reported because they report a valid result (the difference between two close, large concentrations) within the domain of the large uncertainties associated with this kind of measurement. The wide range in measured results for each daughter is in keeping with the high relative dispersions to be expected from the uncertainty discussions of Section 3.4. The histograms of overall unattached fractions in both mines (combined) in Figures 5-8 illustrate the dispersion. To facilitate interpretation, the statistical mean and best estimate of standard deviation for the unattached fraction of each measured radionuclide are given in Table 9 together with the uncertainties in measuring individual concentrations.

For the track mining areas, the average ^{212}Pb unattached fraction is indicated as similar to that of ^{214}Bi and ^{214}Pb but is lower than that of ^{218}Po. For the trackless mining areas, the average ^{212}Pb unattached fraction is also indicated similar to that of ^{214}Bi and ^{214}Pb but lower than that of ^{218}Po. However, the large uncertainties that remain with these average values may be appreciated from the relative standard deviations ranging from 45 to 105%. Indeed although the average value for ^{218}Po is reported as 0.37 and 0.21, for track and trackless areas respectively, there is a high probability that the true unattached fraction in each instance is small.

More definitive estimates of the unattached fractions are available from the few occasions on which the wire screen were also counted. From the data presented in Apendix B and C comparison can be made between unattached fraction of radon and thoron progeny as measured by the two filter and the filter plus wire screen method. Table 11 gives this data for the samples taken. There it can be noticed that the measurements of unattached fraction by the wire-screen method are smaller and more stable than those from the two-filter method. When the unattached fractions of the daughters are averaged individually, the wire-screen method provides estimates ranging from 0.01 to 0.04 whereas the two-filter method provides estimates from 0.02 to 0.15.

For the trackless mining areas in particular, the unattached fractions of ^{218}Po, ^{214}Pb, ^{214}Bi and ^{212}Pb are reasonably estimated by the wire-screen values of 0.03, 0.02, 0.01, and 0.04 respectively since they compare favourably with the results of Busigin, Busigin and Phillips (Bu83) under

similar circumstances. According to the error discussion of Section 3.4, the respective relative uncertainties in these are typically 48% or less. For track mining areas, the unattached fractions can be expected to be a little larger (Bu83).

5.5 Ventilation and 'Age' of the Air

The 'age' of the air (contact time with ore) at each measurement location was estimated from the ratio of radon daughters, and compared with the ventilation period (air residence time) of the measurement site.

In the track mine, the estimated age of the air at site 1 ranged from 25 tp 40 minutes over the first two days, and the residence time in the stope was approximately 12 minutes. On the third day, the ventilation flows were decreased, increasing the residence time to 20 minutes, and the estimated age of the air ranged from 35 to 45 minutes. At site 2, the estimated age of the air ranged from 55 to 60 munutes, with a residence time in the stope of 8 minutes.

In the trackless mine, the estimated age of the air at sites 2. 4, 5 was similar, ranging from 35 to 45 minutes. No daughter ratio measurements were made at site 6, but as it was downstream of those locations in essentially the same air flow, the age would be similar. The residence time at all these locations was one to two minutes, as would be expected for major airways.

The large difference between age of air and residence time at all locations indicates that conditions at the measurement site were set mainly by activities taking place upstream. This is particularly true for the trackless mine, where measurements were made in exhaust airways, downstream of the mining area. The air at all sites had been in contact with ore for at least 30 minutes, as indicated by the radon daughter ratios.

5.6 Comparison With Other Work

A comparison with results from previous investigations into the sizes of particles in uranium mines to which radon daughters are attached is given in Figure 34. The methods used by other investigators vary and aerosol concentration and conditions are often different or not specified. However, the range 50-300 nm seems to be common to all of the reported investigations with the exception of one. The aerosol count median diameter has been reported as 64 nm in French uranium mines (Du78) and 100 nm in Elliot Lake uranium mines (Bu81a); the present results are 55 nm and 69 nm for the track and trackless mines, respectively.

Previous values for the activity size distribution of ^{218}Po, ^{214}Pb and ^{214}Bi are 112, 122, and 118 nm respectively (Du78) and 80, 100, and 92 nm respectively (Bu81a). The mean values for the activity median diameters in this study are lower than these values. However, the median diameter for ^{212}Pb, 100 nm, is similar to the values of 88 and 89 nm reported by Busigin, van der Vooren and Phillips (Bu81a) for the same mines using the same equipment.

Unattached fractions were also measured in these mines by Busigin, Busigin and Phillips (Bu83) using the wire screen method and counting the screen. The unattached fractions were comparable to those estimated in this study. In the track mine they averaged 2.8%, 0.9%, 0.5%, 2.8% for ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{212}Pb respectively. In the trackless mine they averaged 1.5%, 0.7%, 0.0%, and 0.7%.

6. CONCLUSIONS

The count median aerosol diameter in a track mining area was found to be farily constant with time, averaging 55 nm. The median activity diameter of all radon daughters averaged 53 nm, but that of ^{212}Pb was 30% larger at 70 nm.

The count median aerosol diameter in a trackless mining area was found to be variable, due to the passage of vehicles releasing small aerosol particles in the exhaust. The diameter of the background aerosol was in the region of 90 nm, but exhaust aerosols were as small as 32 nm. The activity median diameter was less variable, averaging 84 nm for radon daughters, and 104 nm for ^{212}Pb (i. 25% larger).

The unattached fraction of radon and thoron daughters was low as expected from the high aerosol concentrations.

7. DISCUSSION

The activity median diameter of ^{212}Pb is consistently 25-30% larger than that of the radon progeny. The Phase I literature review suggested that ^{212}Pb would behave differently from radon progeny, but the suggested effects would not be expected to cause ^{212}Pb to attach preferentially to larger aerosol particles than radon progeny. As both radon and thoron progeny size distributions were estimated from measurements on the same filters by the same analysis method, it is unlikely that this difference is the result of measurement errors.

A possible explanation for this difference is not that the ^{212}Pb atoms preferentially attached to larger aerosol particles, but that the particles increased in size after the ^{212}Pb atoms attached. Aerosols in the 100 nm range increase in size with time as particles pick up water molecules and coagulation joins small particles to form larger ones, and so, if the ^{212}Pb carrier aerosol is older than the radon progeny carrier aerosol, it would be expected to be larger.

The half life of ^{212}Pb is so long that almost all of the ^{212}Pb atoms that have attached to particles are present at the measurement site. The time available for coagulation to increase the size of these particles is therefore comparable to the residence time of air in the mine (30-60 minutes). In contrast, the half life of ^{218}Po is so short, the time available for coagulation to increase the size of the particles to which it is attached is only a few minutes, so the effect would be minimal there. If aerosol growth is significant, the activity median diameter of ^{218}Po should be smaller than that of the other longer lived radon progeny. This is supported by measurements in the trackless mine, where the activity median diameter of ^{218}Po was smaller than that of the longer lived ^{214}Bi.

The validity of this suggestion could be tested experimentally in a mine by measuring the relative activity and count diameters of the aerosol at locations in the fresh air supply drifts, workings, and exhaust air drifts. If correct, the thoron activity diameter will grow larger than the radon activity diameters as the residence time in the mine increases. It is possible that the higher initial charge state of ^{212}Pb might lead to higher charges on the attached aerosol particles and hence accelerate coagulation. Any experimental investigation should therefore measure the electrical mobility distribution of the aerosol and of the attached progeny.

The activity median diameters of the radon progeny were found to be similar to the count median diameter of the aerosol. The attachment rate of progeny to particles is proportional to the particle area, and therefore the activity median diameter is usually found to be similar to the area median diameter of the aerosol. If these aerosols are log-normal, the area median diameter would be double the count median diameter. The observed activity median diameters for both radon and thoron progeny are much smaller than that.

There are a number of possible causes for this discrepancy. First, the aerosols may not be log-normal and so the size analysis procedure (which requires log-normality) would give biased results. Second, the shapes of the particles may not be spherical, and so their surface area need not depend on the square of their effective radius, and therefore the estimate of area median diameter is incorrect. Third, coagulation effects might have redistributed the attached progeny at random among the aerosol particles, which would make the activity median diameter similar to the aerosol count median diameter. However, this is unlikely, for the activity median diameter of ^{218}Po is always similar to the count median diameter of the aerosol, and it is unlikely that coagulation would be rapid enough to modify significantly the size distribution of the attached aerosol in the few minutes available before the ^{218}Po decays. Fourth, only a very small fraction (0.01%) of the particles have progeny attached. The median diameter of this aerosol might be smaller than the general aerosol in the measurement location, though this seems unlikely in view of the number of locations used.

Resolution of this question would at least require measurements with 4 or more diffusion batteries to verify that the aerosol distributions were in fact log-normal.

TABLE 1a

Uranium Series (4n+2)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†					
			α		β		γ	
$^{238}_{92}U$	Uranium I	4.51×10^9 y	4.15 4.20	(25%) (75%)	—		—	
$^{234}_{90}Th$	Uranium X_1	24.1 d	—		0.103 0.193	(21%) (79%)	0.063c‡ 0.093c	(3.5%) (4%)
$^{234m}_{91}Pa$	Uranium X_2	1.17 m	—		2.29	(98%)	0.765 1.001	(0.30%) (0.60%)
99.87% | 0.13% $^{234}_{92}U$	Uranium Z	6.75 h	—		0.53 1.13	(66%) (13%)	0.100 0.70 0.90	(30%) (24%) (70%)
$^{234}_{92}U$	Uranium II	2.47×10^5 y	4.72 4.77	(28%) (72%)	—		0.053	(0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^4 y	4.62 4.68	(24%) (76%)	—		0.068 0.142	(0.6%) (0.07%)
$^{226}_{88}Ra$	Radium	1602 y	4.60 4.78	(6%) (95%)	—		0.186	(4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823 d	5.49	(100%)	—		0.510	(0.07%)
$^{218}_{84}Po$	Radium A	3.05 m	6.00	(~100%)	0.33	(~0.019%)	—	
99.98% | 0.02% $^{214}_{82}Pb$	Radium B	26.8 m	—		0.65 0.71 0.98	(30%) (40%) (6%)	0.295 0.352	(19%) (36%)
$^{218}_{85}At$	Astatine	~2 s	6.65 6.70	(6%) (94%)	?	(~0.1%)	—	
$^{214}_{83}Bi$	Radium C	19.7 m	5.45 5.51	(0.012%) (0.008%)	1.0 1.51 3.26	(23%) (40%) (19%)	0.609 1.120 1.764	(47%) (17%) (17%)
99.98% | 0.02% $^{214}_{84}Po$	Radium C'	164 us	7.69	(100%)	—		0.799	(0.014%)
$^{210}_{81}Tl$	Radium C''	1.3 m	—		1.3 1.9 2.3	(25%) (56%) (19%)	0.296 0.793 1.31	(80%) (100%) (21%)
$^{210}_{82}Pb$	Radium D	21 y	3.72	(.000002%)	0.016 0.061	(83%) (15%)	0.047	(4%)
$^{210}_{83}Bi$	Radium E	5.01 d	4.65 4.69	(.00007%) (.00005%)	1.161	(~100%)	—	
~100% | .0001% $^{210}_{84}Po$	Radium F	138.4 d	5.305	(100%)	—		0.803	(0.0011%)
$^{206}_{81}Tl$	Radium E''	4.19 m	—		1.571	(100%)	—	
$^{206}_{82}Pb$	Radium G	Stable	—		—		—	

* This expression describes the mass number of any member in this series, where n is an interger.
Example: $^{206}_{82}Pb$ (4n + 2).....4(51) + 2 = 206

† Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.

‡ Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and USNRDL-TR-802.

TABLE 1b

Thorium Series (4n)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†					
			α		β		γ	
$^{232}_{90}Th$	Thorium	1.41×10^{10} y	3.93 4.01	(24%) (76%)	—		—	
$^{228}_{88}Ra$	Mesothorium I	6.7 y	—		0.055	(100%)	—	
$^{228}_{89}Ac$	Mesothorium II	6.13 h	—		1.18 1.75 2.09	(35%) (12%) (12%)	0.34ef 0.908 0.96c	(13%) (25%) (20%)
$^{228}_{90}Th$	Radiothorium	1.910 y	5.34 5.43	(28%) (71%)	—		0.084 0.214	(1.6%) (0.3%)
$^{224}_{88}Ra$	Thorium X	3.64 d	5.45 5.68	(6%) (94%)	—		0.241	(3.7%)
$^{220}_{86}Rn$	Emanation Thoron (Tn)	55 s	6.29	(100%)	—		0.55	(0.07%)
$^{216}_{84}Po$	Thorium A	0.15 s	6.78	(100%)	—		—	
$^{212}_{82}Pb$	Thorium B	10.64 h	—		0.346 0.586	(81%) (14%)	0.239 0.300	(47%) (3.2%)
$^{212}_{83}Bi$	Thorium C	60.6 m	6.05 6.09	(25%) (10%)	1.55 2.26	(5%) (55%)	0.040 0.727 1.620	(2%) (7%) (1.8%)
64.0%		36.0%						
$^{212}_{84}Po$	Thorium C'	304 ns	8.78	(100%)	—		—	
$^{208}_{81}Tl$	Thorium C''	3.10 m	—		1.28 1.52 1.80	(25%) (21%) (50%)	0.511 0.583 0.860 2.614	(23%) (86%) (12%) (100%)
$^{208}_{82}Pb$	Thorium D	Stable	—		—		—	

* This expression describes the mass number of any member in this series, where n is an integer.

Example: $^{232}_{90}Th$ (4n).....4(58) = 232

† Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.

‡ Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Lederer, C.M., Hollander, J.M., and Perlman, I., Table of Isotopes (6th ed.; New York: John Wiley & Sons, Inc., 1967) and Hogan, O.J., Zigman, P.E., and Mackin, J.L., Beta Spectra (USNRDL-TR-802 [Washington, D.C.: U.S. Atomic Energy Commission, 1964]).

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TABLE 2

Comparison of Uncertainties in Measurement for the Two Counting Schemes Used

Counting scheme	Relative Standard Deviation %			
	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb
2-5, 9-25, 40-70, 360-460*	28.7	6.6	17.3	5.3
2-5, 9-25, 30-60, 360-460**	31.6	7.4	20.2	5.3

* Assumptions: Sample Time = 10 min.; V = 3 L/min; f_u = 0.05;
Radon progeny concentrations per pCi/L:
^{218}Po: ^{214}Pb: ^{214}Bi: ^{212}Pb: ^{212}Bi = 100: 60: 40: 2: 1

TABLE 3

Dimensions of Diffusion Batteries

D.B. no.	No. of channels	Width (cm)	Length (cm)	Spacing between plates (cm)
3	25	10	19	0.08
4	50	10	30	0.04
5	140	10	43	0.04

TABLE 4

Uncertainties in Concentrations using Four or Five Counting Intervals

Sampling Time (min)	Counting Scheme	Measurement	Species	Relative Standard Deviation (%)
10	2-4,9-12,85-95,240-250*	Diffusion Batteries	^{218}Po	24.5
			^{214}Pb	6.9
			^{214}Bi	13.3
			^{212}Pb	7.9
10	2-5,9-25,40-70,360-460**	Unattached Fractions	^{218}Po	35.3
			^{214}Pb	7.7
			^{214}Bi	19.5
			^{212}Pb	7
10	2-4,9-12,85-95,240-250* and 650-750	Concentration of five radionuclides	^{218}Po	25
			^{214}Pb	10.7
			^{214}Bi	13.4
			^{212}Pb	5.5
			^{212}Bi	308

* Assumptions: V = 3 L/min; radon progeny concentration per pCi/L: ^{218}Pb: ^{214}Pb: ^{214}Bi: ^{212}Pb: ^{212}Bi: = 100:60:40:2:1

** Assumptions: V = 7 L/min; f_u = 0.05; ^{218}Pb:^{214}Pb:^{214}Bi: ^{212}Pb:^{212}Bi = 100:60:40:2:1 per pCi/L

TABLE 5

Uncertainties in Concentrations Using One or Two-Count Scheme

Sampling Time	Counting Scheme*	Measurement	Species	RSD (%)	Accuracy (over- or under estimation) (%)
5	2-7	Diff. Batt. Unatt. Fractions	RnWL	6.8	16
15	330-345	Diff. Batt.	^{212}Pb	9	0.9
15	330-360	Unatt. Fractions	^{212}Pb	8.8	0.2
15	270-300	Unatt. Fractions	^{212}Pb	8.4	12
15	270-285	Diff. Batt.	^{212}Pb	8.6	15
10	2-7,340-350	Working Level	RnWL	6.7	4.3
			TnWL	9.8	0.1

* Assumptions: V = 3 L/min; f_u = 0.05; ^{218}Pb: ^{214}Pb: ^{214}Bi: ^{212}Pb: ^{212}Bi = 100:60:40:2:1 per pCi/L

TABLE 6a - Conditions during Sampling in Track Mine

Date / Location	Sample Time	Measurement	Average Temperature (°C)	Average Relative Humidity (%)	Average Condensation Nuclei Count ($10^3/cm^3$)	Ventilation Rate (CFM)	Comments
Jan.29	9:00	DB	11.0	78	N/A	13,000	Drilling in Stope
	9:15	DB	10.8	79		13,400	None
	11:05	UF	11.0	82		16,000	None
Exhaust Exit of Active Stope	11:22	WL	11.0	81		16,000	None
	11:40	UF	11.0	81		14,400	None
	13:15	UF	10.8	82		13,100	Drilling in Stope
	13:38	WL	10.8	82		14,400	Drilling in Stope
Jan. 30	8:45	DB	10.6	81	51	15,000	Drilling in Stope
	9:00	DB	10.8	80	64	14,700	Drilling in Stope
(as on Jan.29)	10:50	UF	10.8	85	41	13,100	None
	11:07	WL	10.8	85	44	13,100	Drilling in Stope
	11:25	UF	10.8	85	60	14,700	Drilling in Stope
	13:00	UF	10.6	85	46	16,000	Drilling in Stope
	13:23	WL	10.6	84	41	16,000	None
Jan.31	8:55	DB	11.2	85	41	10,500	Drilling in Stope
	9:10	DB	11.1	85	51	10,500	Drilling in Stope
	11:00	UF	11.0	88	30	12,800	None
(as on Jan.29)	11:17	WL	11.0	88	30	9,000	None
	11:35	UF	11.1	87	42	7,000	None
	13:20	UF	11.2	88	41	7,500	Drilling 15 min.before Sample
	13:33	WL	11.2	88	36	7,400	None
Feb.1	9:25	DB	11.8	65	70	16,500*	
	9:40	DB	11.8	65	71	↓	* Average (fairly steady)
	11:30	UF	11.2	68	66		
Exhaust Way above inactive (ie.older) Mine Area.	11:47	WL	11.2	68	69		
	12:05	UF	11.2	68	71		
	13:50	UF	11.1	67	73		
	14:03	WL	11.1	67	73		

TABLE 6b - Conditions during Sampling in Trackless Mine

Location \ Date	Sample Time	Measurement	Average Temperature (°C)	Average Relative Humidity (%)	Average Condensation Nuclei Count ($10^3/cm^3$)	Ventilation Rate (CFM)	Comments
Feb.4	8:40	DB	14.0	72	183	264,000*	1 Vehicle passed by
	8:55	DB	14.0	72	-		1 Vehicle passed by
	10:45	UF	14.0	75	130		3 Vehicles passed by
Main Exhaust Drift by Electrical Sub-station - well travelled route	11:02	WL	14.0	75	140		2 Vehicles passed by
	11:20	UF	14.0	75	120		None
	13:00	UF	13.9	76	125		1 Vehicle passed by
	13:18	WL	13.9	76	110	*average (fairly steady)	None
Feb.5	8:40	DB(Ref + #5)	15.0	86	130	7,000-25,000*	1 Vehicle passed by
	8:50	DB(#3 + #4)	15.0	86	119		None
	10:40	UF	15.0	81	137		1 Vehicle passed by
Exhaust Drift in Waste Rock Storage Area - well travelled route	11:02	WL	15.0	81	183		1 Vehicle passed by
	11:15	UF	15.0	81	-		-
	13:05	UF	15.0	81	143		1 Vehicle passed by
	13:18	WL	15.1	81	194	*turbulent and variable	2 Vehicles passed by
Feb.6	9:00	DB	12.3	85	109	122,000	Pond of Water around Fans
	9:15	DB	12.4	86	125	112,000	(Water whipped into Air)
Exhaust Drift in Waste Rock Storage Area not used by Vehicles	11:05	UF	12.5	85	135	117,000	
	11:22	WL	12.5	85	110	107,000	no Vehicles during sampling
	11:40	UF	12.5	85	136	107,000	
	13:25	UF	12.4	85	156	115,000	
	13:38	WL	-	-	-	-	

TABLE 6b (cont'd) - Conditions during Sampling in Trackless Mine

Date / Location	Sample Time	Measurement	Average Temperature (°C)	Average Relative Humidity (%)	Average Condensation Nuclei Count (10^3/cm^3)	Ventilation Rate (CFM)	Comments
Feb.7	8:40	DB (ThB)	12.5	83	143	105,000	
	8:55	UF (ThB)	12.5	83	119	105,000	Jeep parked downwind 3 min.
Exhaust Drift (as on Feb.6) - Work done to remove Water from around fans located upwind	9:10	DB (RnWL)	12.6	84	134	105,000	
	9:20	UF (RnWL)	12.6	84	143	105,000	
	9:40	DB (RnWL)	12.6	84	121	105,000	Upwind Airline opened
	9:50	UF (RnWL)	12.6	84	170	103,000	
	10:10	DB (RnWL)	12.9	84	179	101,000	2 Trucks pass operate upwind
	10:20	UF (RnWL)	12.9	84	134	101,000	↓
	10:40	DB (RnWL)	12.9	84	138	99,000	
	10:55	UF (RnWL)	12.8	85	128	97,000	
	12:05	DB (ThB)	13.1	80	121	118,000	Trucks gone Water removed
	12:25	UF (ThB)	13.1	80	152	105,000	
	12:45	UF (ThB)	13.2	79	160	105,000	
	13:15	DB (ThB)	13.2	78	164	105,000	
	13:40	DB (ThB)	13.2	78	166	105,000	Bulldozer operated downwind prior to sampling
	14:00	UF (ThB)	-	-	-	-	
Feb.8	8:25	UF (ThB)	13.2	78	125	106,000	Drift Walls drying
	8:45	DB (RnWL)	13.2	78	155	102,000	
	9:15	DB (RnWL)	13.1	77	117	94,000	
Exhaust Drift (as on Feb.7) - Water removed from around fans	9:25	UF (RnWL)	13.1	77	127	94,000	Jeep running 20 ft. downwind
	9:55	UF (RnWL)	13.1	78	118	102,000	
	12:00	UF (ThB)	13.2	78	128	100,000	
	12:20	UF (ThB)	13.2	78	127	98,000	
	13:35	UF (ThB)	13.2	78	150	98,000	

TABLE 7a

Concentrations and Working Levels of Radon/Thoron Progeny (Track)

Date	Time	Concentrations (pCi/L)				Concentration Ratios	Age of air (min) (approximate, from (Ev69))	Working Level* (from measured concentrations)		Working Level** (Grab sample)		
		^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb			RnWL	TnWL	Time	RnWL	TnWL
Jan 29	9.00	25.8	11.6	5.9	1.25	100:45:22:5	30	0.11	0.15	11.22	0.09	0.12
	9.15	22.6	8.4	8.3	1.42	100:37:37:6	25	0.10	0.17	13.38	0.08	0.09
	11.35	24.4	10.5	4.7	1.02	100:43:19:4	30	0.10	0.12			
Jan 30	8.45	21.2	8.5	4.5	1.09	100:40:21:5	25	0.08	0.13	11.07	0.11	0.15
	9.00	13	8	7.9	1.13	100:61:61:9	40	0.08	0.14	13.23	0.09	0.12
	10.50	30.6	13.9	7.3	1.34	100:45:24:4	30	0.13	0.16			
	11.25	24	13.4	7.8	1.29	100:56:32:5	35	0.12	0.16			
	13.00	23.5	10.9	6	0.99	100:46:25:4	30	0.10	0.12			
Jan 31	8.55	24.4	12.9	7.8	1.21	100:53:32:5	40	0.12	0.15	11.17	0.14	0.17
	9.10	16.5	11	10.3	1.25	100:67:62:7	45	0.11	0.15	13.33	0.20	0.20
	11.00	29.2	14.6	8.2	1.2	100:50:28:4	35	0.13	0.15			
	11.35	35.1	17.5	9.2	1.49	100:50:26:4	35	0.16	0.18			
	13.20	42.9	23.9	13.86	1.78	100:56:30:4	35	0.21	0.22			
Feb 1	9.25	58	44	35	3.25	100:76:60:6	60	0.41	0.40	11.47	0.55	0.49
	9.40	40.4	34.4	47†	3.55	-	--	0.39	0.44	14.03	0.48	0.35
	11.30	67.7	50.8	41.6	3.24	100:75:61:5	60	0.48	0.40			
	12.05	71.1	54.3	44.1	3.36	100:76:62:5	60	0.51	0.41			
	13.50	75	51.5	39.6	2.91	100:69:53:4	55	0.49	0.36			

* Calculated as: $RnWL = \frac{1.03\ C_{^{218}Po} + 5.07\ C_{^{214}Pb} + 3.73\ C_{^{214}Bi}}{100}$

$TnWL = \frac{123.19\ C_{^{212}Pb}}{1000}$ (The second term, $0.13\ C_{^{212}Bi}$, in the TnWL formula is ignored because the concentration of ^{212}Bi could not be measured with acceptable accuracy.)

** Calculated as: $RnWL = \frac{I\ (2\text{-}7)}{50 \times 235 \times V \times \eta}$

$TnWL = \frac{I\ (340\text{-}350)}{100 \times 13 \times V \times \eta}$ (All terms defined in the text)

† Physically impossible situation. Data ignored.

TABLE 7b

Concentrations and Working Levels of Radon/Thoron Progeny (Trackless)

Date	Time	Concentrations (pCi/L) ^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb	Concentration Ratios	Age of air (min) (approximate, from (Ev69))	Working Level* (from measured concentrations RnWL	TnWL	Working Level** (Grab sample) Time	RnWL	TnWL
Feb 4	8.40	72.2	36.3	24.4	2.41	100:50:34:3	35	0.35	0.30	11.02	0.36	--
	8.55	52.6	25.2†	28.6	2.27	--	--	0.29	0.28			
	10.45	66.2	38.3	25.3	2.2	100:58:38:3	40	0.36	0.27			
	11.20	61.5	38.1	25.6	2.4	100:62:42:4	40	0.35	0.30			
	13.00	84.2	47.8	15.5	2.2	100:57:18:3	35	0.39	0.27			
Feb 5	8.40	21.7†	41.3	37.5	1.87	--	--	0.37	0.23	11.02	0.24	0.21
	10.40	47.5	28.5	19.3	1.67	100:60:41:3	45	0.26	0.21	13.18	0.29	0.22
	11.15	54.9	27.9	16.7	1.66	100:51:30:3	35	0.26	0.20			
	13.05	62.7	30.8	18.3	1.71	100:49:29:3	30	0.29	0.21			
Feb 6	9.00	53.4	30.5	20	1.72	100:57:37:3	40	0.28	0.21	11.22	0.31	0.20
	9.15	32.3	18.7†	25.3	2.04	--	--	0.20	0.25	13.38	0.31	0.19
	11.05	61.6	34	23	1.66	100:55:37:3	40	0.32	0.20			
	11.40	51	32.6	23.6	1.52	100:64:46:3	45	0.31	0.19			
	13.25	57.5	32.4	23.3	1.87	100:56:40:3	40	0.31	0.23			

* Calculated as: $RnWL = \frac{1.03\ C_{^{218}Po} + 5.07\ C_{^{214}Pb} + 3.73\ C_{^{214}Bi}}{100}$

$TnWL = \frac{123.19\ C_{^{212}Pb}}{1000}$ (The second term, $0.13\ C_{^{212}Bi}$, in the TnWL formula is ignored because the concentration of ^{212}Bi could not be measured with acceptable accuracy.)

** Calculated as: $RnWL = \frac{I\ (2\text{-}7)}{50 \times 235 \times V \times \eta}$

$TnWL = \frac{I\ (340\text{-}350)}{100 \times 13 \times V \times \eta}$ (All terms defined in the text)

† Physically impossible situation. Data ignored.

TABLE 7c

Working Levels of Radon/Thoron Progeny and ^{212}Pb Concentrations Obtained by One-Count Method[1]

Date	Time	RnWL	TnWL	^{212}Pb concentration[2] (pCi/L)
Feb 7	8.40	--	0.22[3]	1.8
	8.55	--	0.22[3]	1.8
	9.10	0.37	--	-
	9.20	0.36	--	-
	9.40	0.33	--	-
	9.50	0.30	--	-
	10.10	0.33	--	-
	10.20	0.32	--	-
	10.40	0.28	--	-
	10.55	0.34	--	-
	12.05	--	0.20	1.7
	12.20	--	0.20	1.7
	12.40	--	0.20	1.7
	13.15	--	0.20	1.7
	13.40	--	0.19	1.6
	13.55	--	0.20	1.7
Feb 8	8.30	--	0.20[3]	1.6
	8.45	0.27	--	-
	8.55	0.30	--	-
	9.15	0.28	--	-
	9.35	0.28	--	-
	9.55	0.34	--	-
	12.00	--	0.20	1.7
	12.20	--	0.19	1.6
	13.30	--	0.19	1.6

[1] The method is described in Section 2.
[2] The calculation procedure for these is described in Section 2.
[3] Slightly overestimated due to modified counting interval in order to enable counting within the allowed working period.

TABLE 8a

Unattached Fraction, Activity and Aerosol Size Distributions for Track-type Mine

Date	Unattached Fractions					Activity Size Distributions†					Aerosol Size Distributions		
	Time	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb	Time	^{218}Po	^{214}Pb (GSD)	^{214}Bi	^{212}Pb	Time	Count Median dia. (μm)	GSD
Jan 29*	--	--	--	--	--	9.00	--	--	--	0.065 (2.69)	--	--	
	--	--	--	--	--	9.15	--	--	--	0.064 (2.42)	--	--	
Jan 30	10.50	0.10	0.35	0.36	0.24	8.45	0.053 (2.21)	0.047 (1.59)	0.043 (2.43)	0.057 (2.30)	9.40	0.051	2.34
	11.25	0.43	0.34	0.34	0.34						11.40	0.053	1.52
	13.00	0.42	0.26	0.33	0.10	9.00	0.063 (2.62)	0.056 (1.51)	0.059 (1.34)	0.072 (2.47)	12.50	0.050	2.68
											13.50	0.051	2.14
Jan 31	11.00	0.00	0.00	0.27	0.03	8.55	--	0.054 (2.16)	0.057 (2.40)	0.082 (2.55)	9.35	0.062	2.42
	11.35	0.78	0.11	-0.17	0.15						10.00	0.065	1.40
	13.20	0.29	0.19	0.15	0.25	9.10	--	0.044 (2.47)	0.060 (2.19)	0.10 (1.75)	11.50	0.058	2.19
											13.00	0.061	1.72
											14.05	0.072	2.56
Feb 1	11.30	-0.06	0.19	0.23	0.20	9.40	0.047 (2.29)	0.047 (1.54)	0.053 (1.45)	0.058 (1.89)	10.25	0.046	1.60
	12.05	0.84	0.08	0.23	0.20						12.20	0.050	1.76
	13.50	0.44	0.28	0.12	0.26						13.25	0.048	1.56

* Exact pump flow rates were not known for each sample. Most data had to be rejected because of unknown errors. Condensation nuclei counters malfunctioned. Aerosol concentration data were, therefore, also rejected.

† The listed values are for the median diameters (in μm) of the activity size distributions for specified radionuclides. The geometric standard deviations are given in brackets below each diameter.

TABLE 8b

Unattached Fraction, Activity and Aerosol Size Distributions for Trackless Mine

Date	Unattached Fractions					Activity Size Distributions †					Aerosol Size Distributions		
	Time	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb	Time	^{218}Po	^{214}Pb (GSD)	^{214}Bi	^{212}Pb	Time	Count Median dia. (μm)	GSD
Feb 4	10.45	0.26	0.13	0.02	0.08	8.40	0.084	0.091	0.096	—	9.30	0.088	1.84
	11.20	0.13	0.11	0.17	0.15		(2.06)	(1.48)	(2.09)		12.40	0.094	1.43
	13.00	0.30	0.25	0.36	0.29								
Feb 5*	10.40	-0.02	0.11	0.24	0.11	8.40	—	0.053	0.078	0.092	9.20	0.070	1.15
	11.15	-0.02	0.04	0.10	-0.02			(2.76)	(2.50)	(1.29)	11.50	0.084	1.48
	13.05	0.30	0.12	-0.03	0.08						12.50	0.032	2.50
Feb 6	11.05	0.54	0.22	0.16	0.25	9.00	0.066	0.073	0.077	0.09	9.45	0.062	1.55
	11.40	-0.06	0.16	0.19	0.02		(2.40)	(1.81)	(1.75)	(2.23)	12.00	0.047	1.98
	13.25	0.48	0.03	0.07	0.14	9.15	0.069	—	0.089	0.10	13.05	0.076	1.41
							(1.29)		(1.56)	(2.68)			
	Time	RnWL		Time	^{212}Pb	Time	RnWL	(GSD)	Time	^{212}Pb (GSD)			
Feb 7**	9.20	0.06		8.55	0.06	9.10	0.097	(1.84)	8.40	0.125			
	9.50	0.09		12.25	0.05	9.40	0.085	(1.86)		(1.68)			
	10.20	0.26		12.45	0.22	10.10	0.089	(2.55)	13.15	0.107			
	10.55	0.16		14.00	0.05	10.40	0.096	(1.81)		(1.65)			
									13.40	0.106			
										(1.62)			
Feb 8††	8.55	0.24		8.25	0.12	8.45	0.079	(1.65)	—	—	10.04	0.07	1.5
	9.25	0.10		12.00	0.22	9.15	0.089	(1.58)			10.20	0.07	1.43
	9.55	0.15		12.20	0.21								
				13.35	0.12								

* Samples through DB#3 and #4 taken 10 minutes after samples through DB#5 and reference (Track passed during first samples only)

** No suitable time slot was available to measure aerosol size distributions.

† Explained in footnotes to Table 7a.

†† Data for activity size distributions of ^{212}Pb had to be rejected because of pump failure.

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TABLE 9

Statistical Means, Best Estimates of Standard Deviations and Uncertainties in Concentration Measurements for the Unattached Fractions

Mine	Mean unattached fractions $\pm\sigma_{n-1}$ (uncertainties in concentration measurements are given in brackets)				
	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb	RnWL
Track	0.37 ± 0.30	0.21 ± 0.10	0.21 ± 0.16	0.20 ± 0.09	--
	(±0.29 - 0.32)	(±0.07)	(±0.17 - 0.20)	(±0.05)	(±0.07)
Trackless	0.21 ± 0.22	0.13 ± 0.07	0.14 ± 0.12	0.13 ± 0.09	0.15 ± 0.08

TABLE 10

Median Diameters for all Measured Size Distributions in the Present Work

Mine	Mean value of median diameter (um) ± σ_{n-1}					
	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb	RnWL	Aerosol
Track	0.054 ± 0.008	0.05 ± 0.005	0.054 ± 0.007	0.07 ± 0.015	--	0.055 ± 0.008
Trackless	0.073 ± 0.01	0.07 ± 0.02	0.085 ± 0.009	0.1 ± 0.013	0.089 ± 0.007	0.069 ± 0.019

TABLE 11

Comparison of Unattached Fractions as Measured by the Two Filter Counting and the Filter & Wire Screen Counting Methods

DATE	Unattached Fraction					
	Time	Method	^{218}Po	^{214}Pb	^{214}Bi	^{212}Pb
Feb. 4	11:20	Ref + BU*	0.13	0.11	0.17	0.15
		Ref + WS**	0.06	0.03	0.002	0.06
Feb. 5	11:15	Ref + BU*	-0.02	0.04	0.10	-0.02
		Ref + WS**	-0.001	0.01	0.02	0.04
Feb. 6	11:40	Ref + BU*	-0.06	0.16	0.19	0.02
		Ref + WS**	0.02	0.01	0.01	0.02
Average Unattached Fractions		Ref + BU*	0.02	0.10	0.15	0.05
		Ref + WS**	0.03	0.02	0.01	0.04

* Calculated as: $f_u = \frac{C_{ref} - C_{back\text{-}up}}{EC_{ref}}$ (as per Section 2, Equation 4)

** Calculated as: $f_u' = \frac{C_{ws}}{KEC_{ref}}$ where: C_{ws} = concentration on wire screen
K = relative counting efficiency = 0.5 (Ge 72)

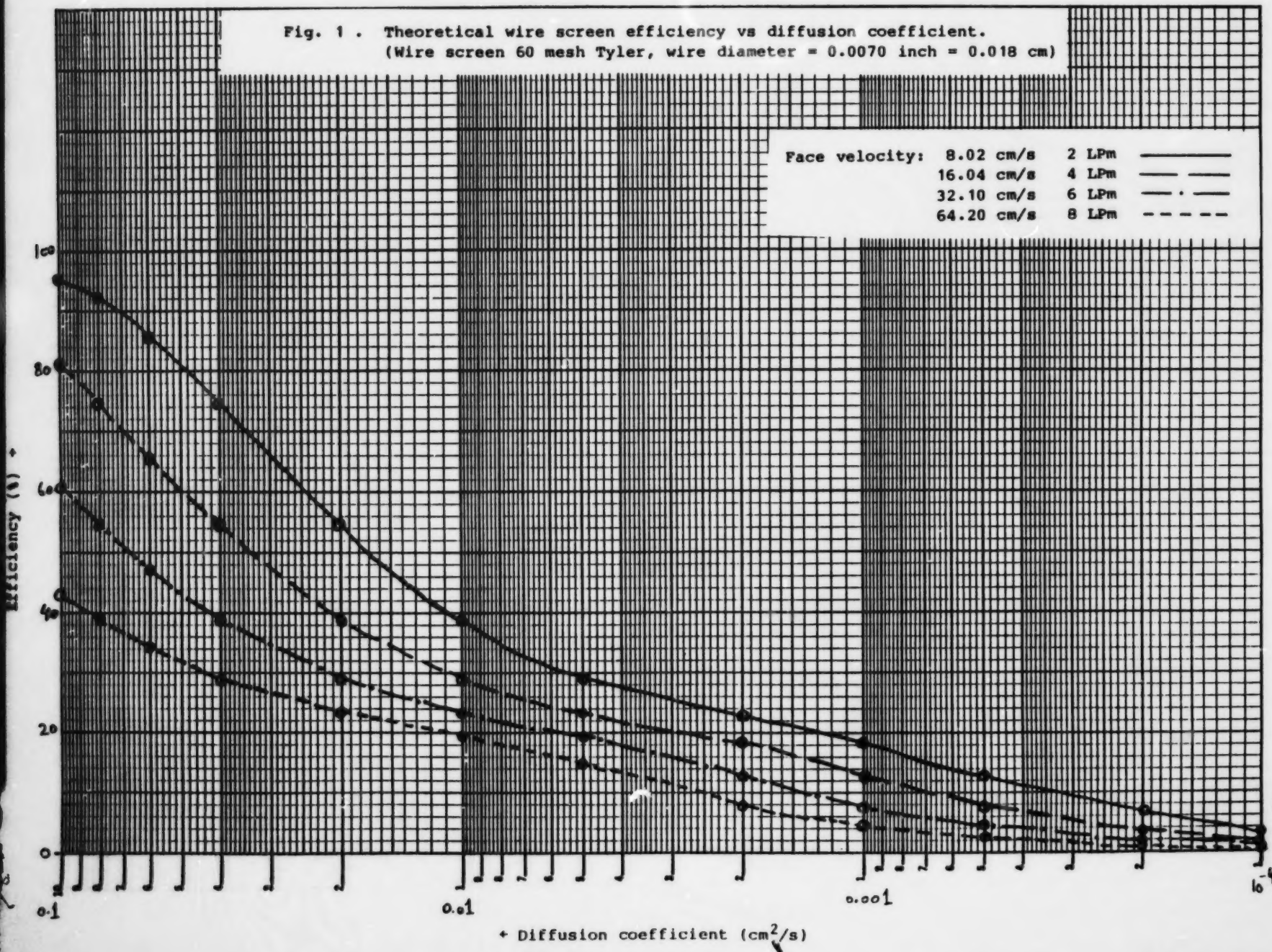


Fig. 1 . Theoretical wire screen efficiency vs diffusion coefficient.
(Wire screen 60 mesh Tyler, wire diameter = 0.0070 inch = 0.018 cm)

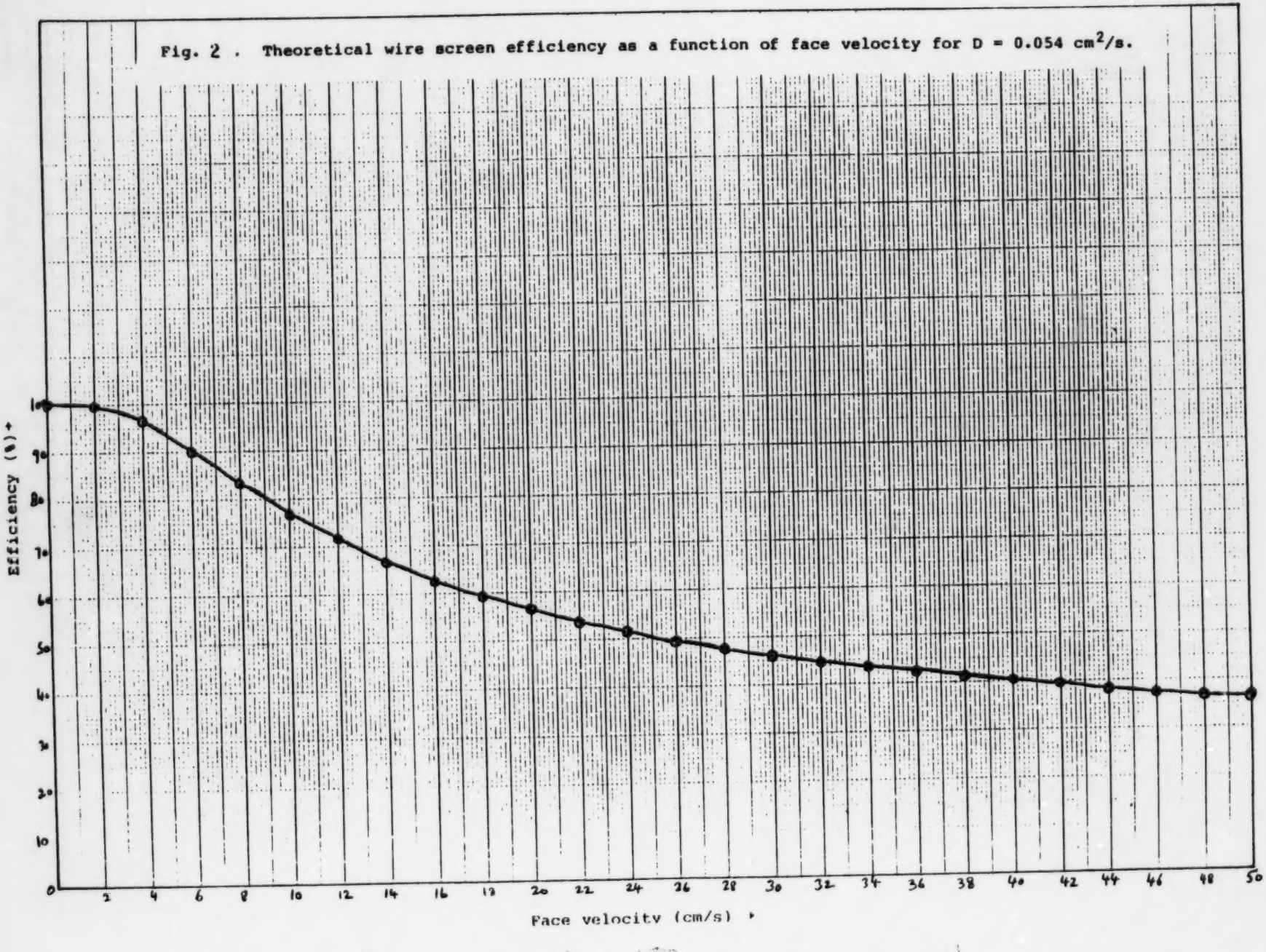
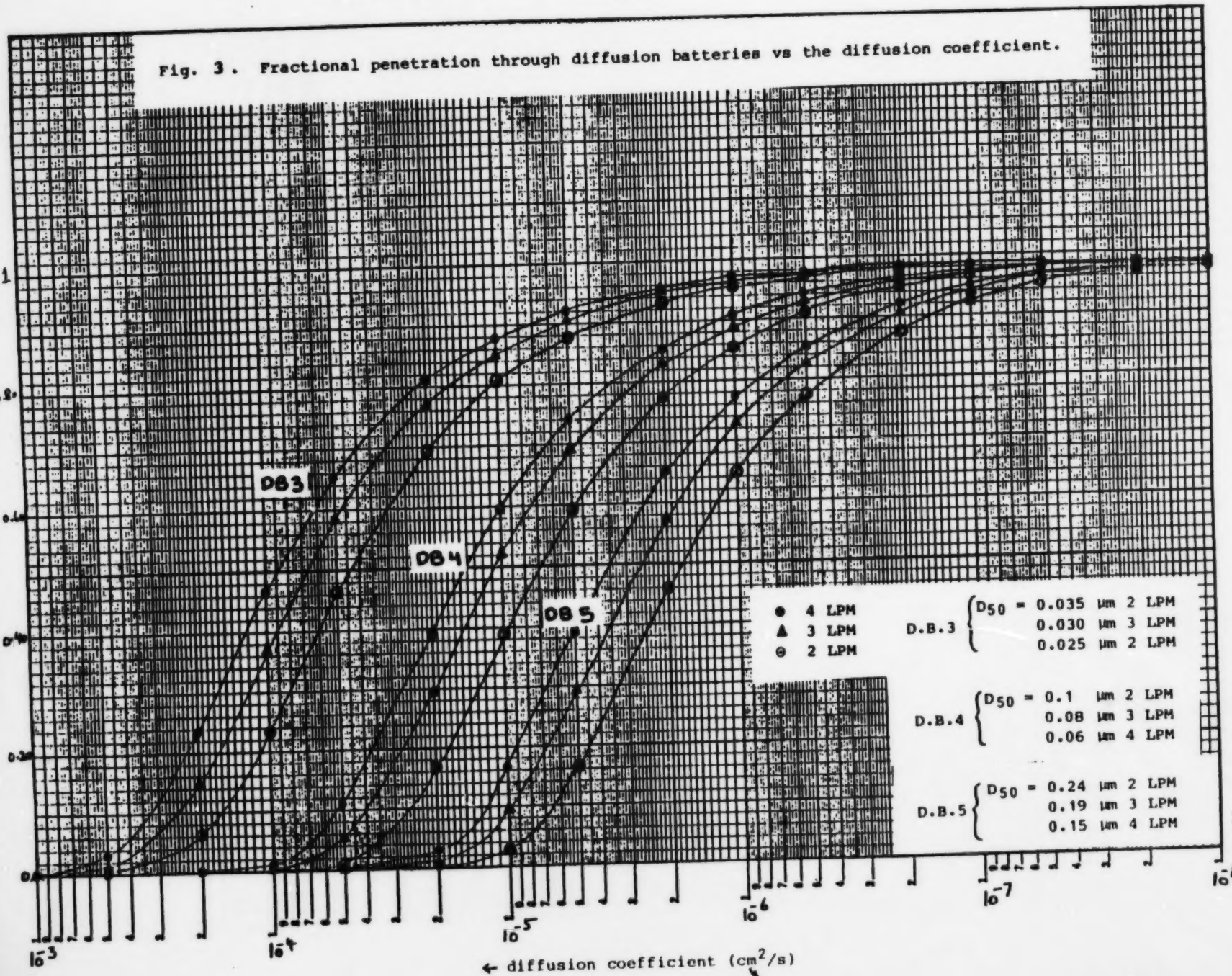


Fig. 2 . Theoretical wire screen efficiency as a function of face velocity for D = 0.054 cm^2/s.

Fig. 3. Fractional penetration through diffusion batteries vs the diffusion coefficient.



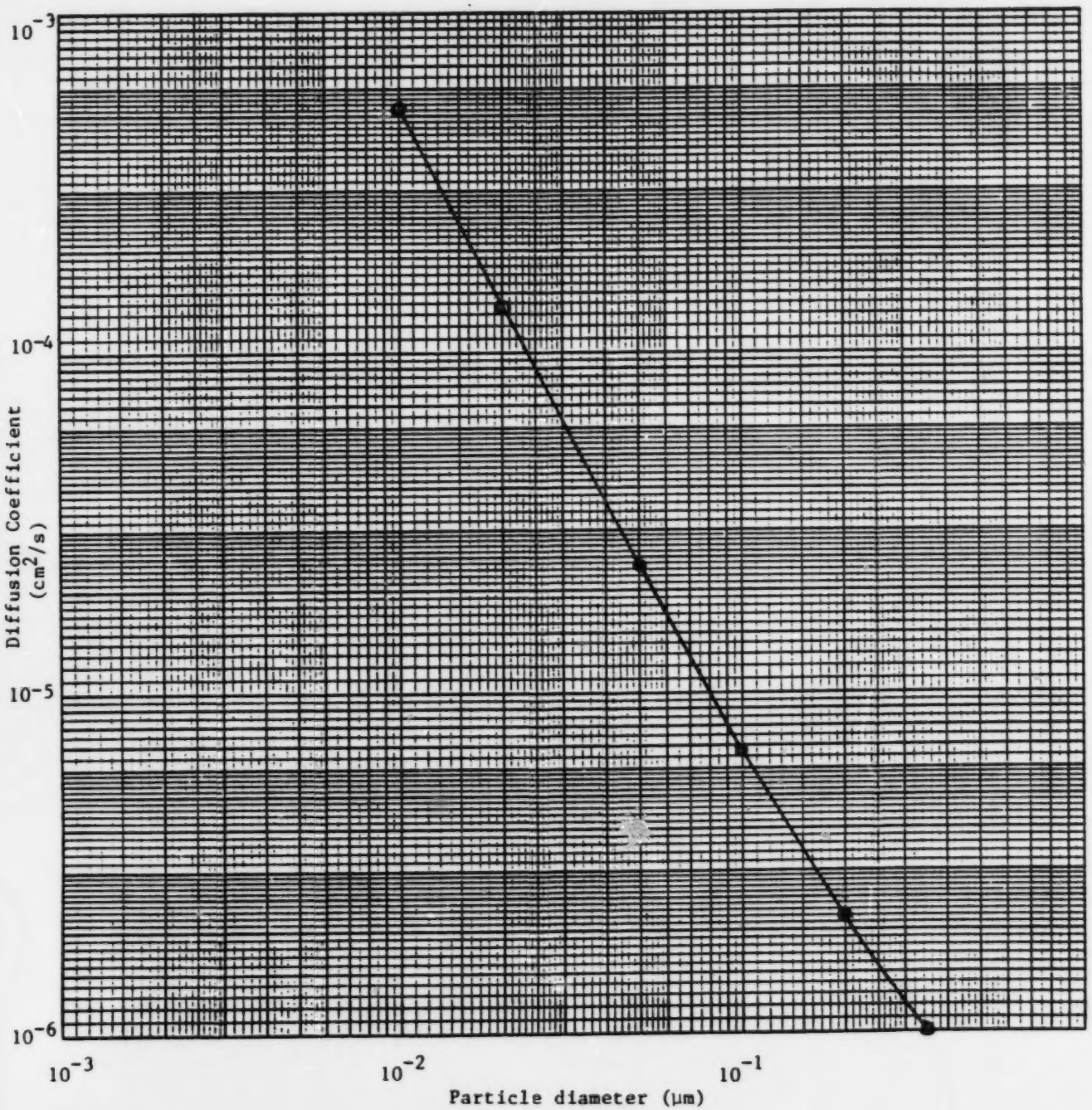


Fig. 4. Particle size relationship to the diffusion coefficient in the size range relevant to this work (Fr77).

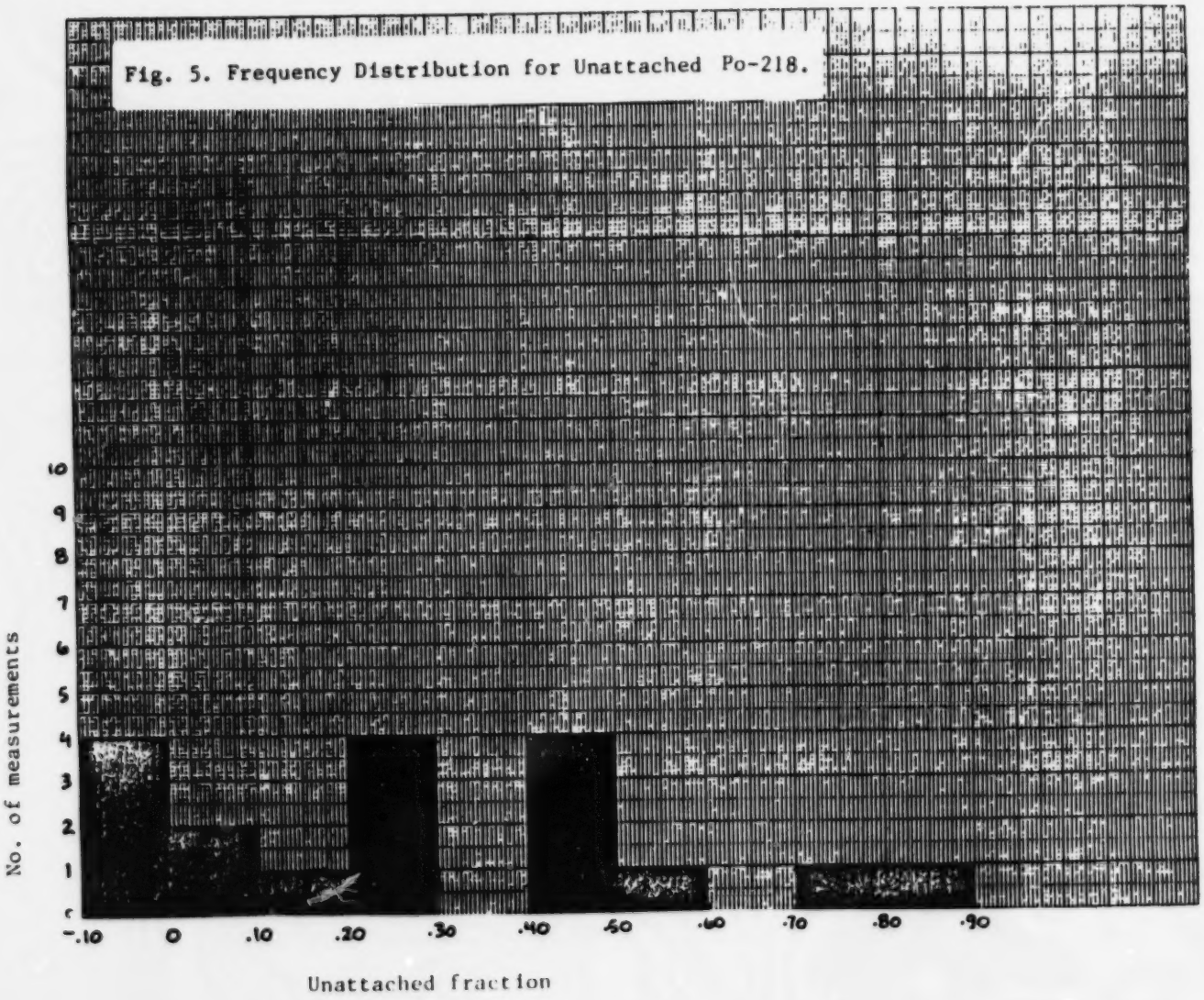


Fig. 5. Frequency Distribution for Unattached Po-218.

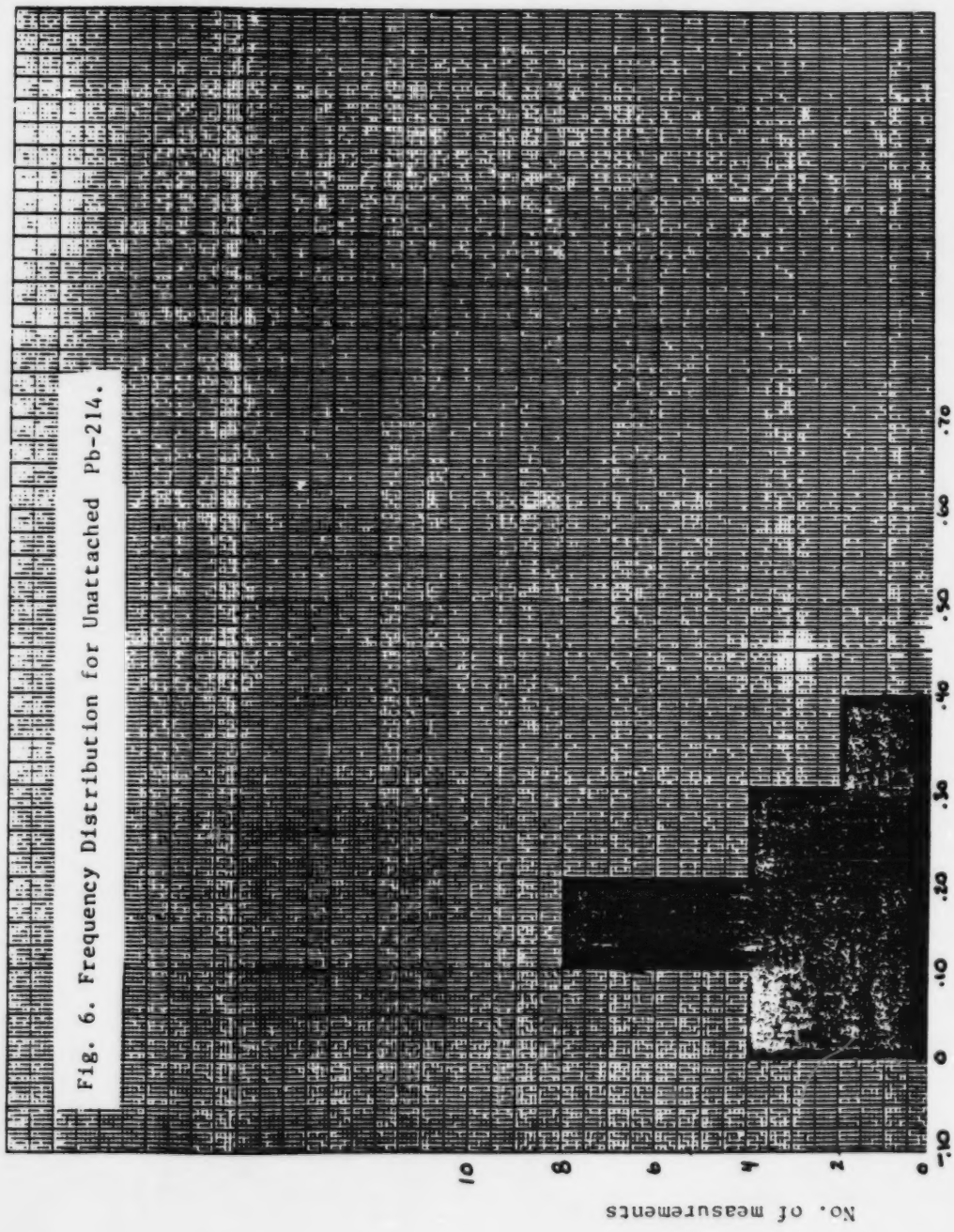


Fig. 6. Frequency Distribution for Unattached Pb-214.

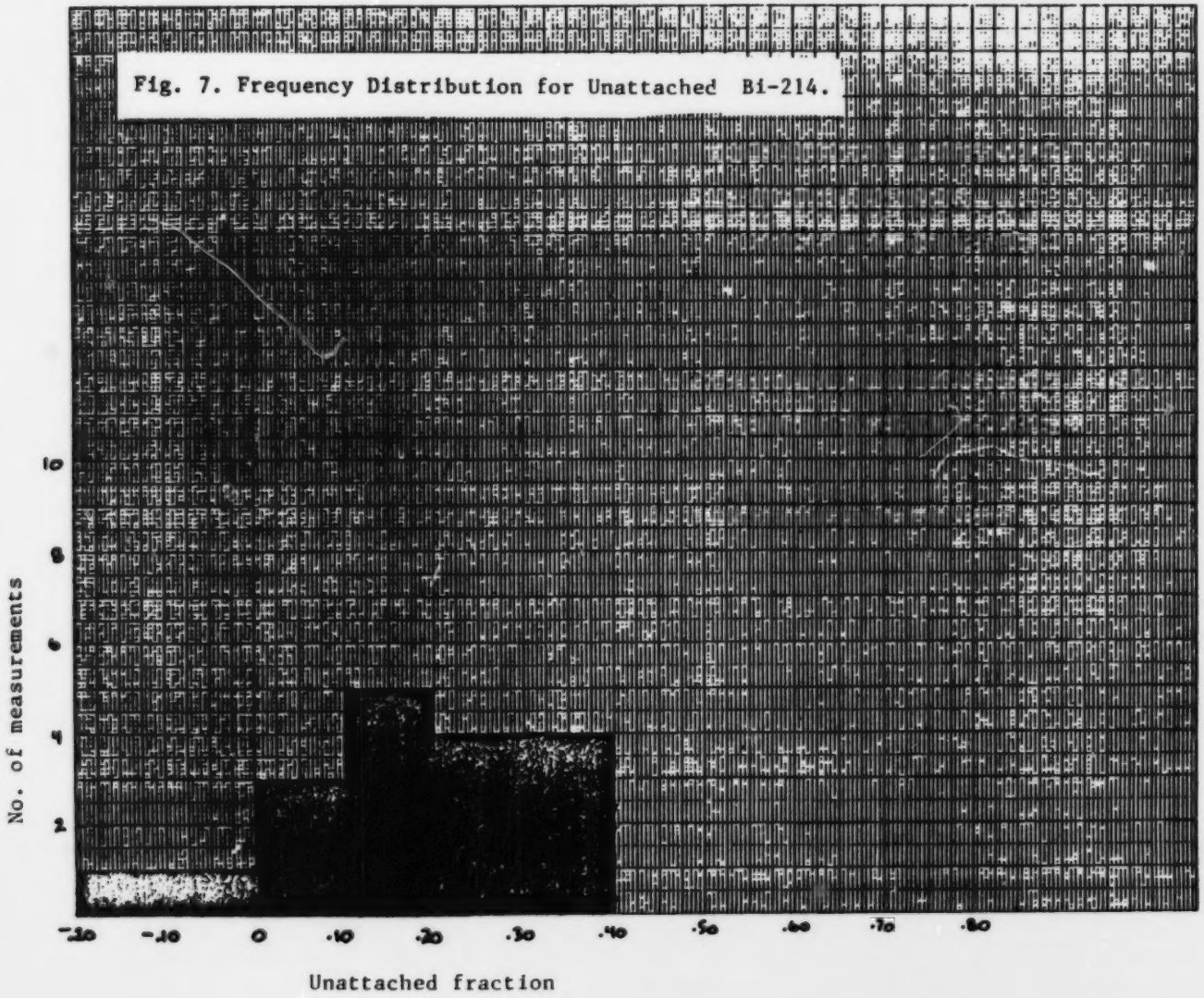


Fig. 7. Frequency Distribution for Unattached Bi-214.

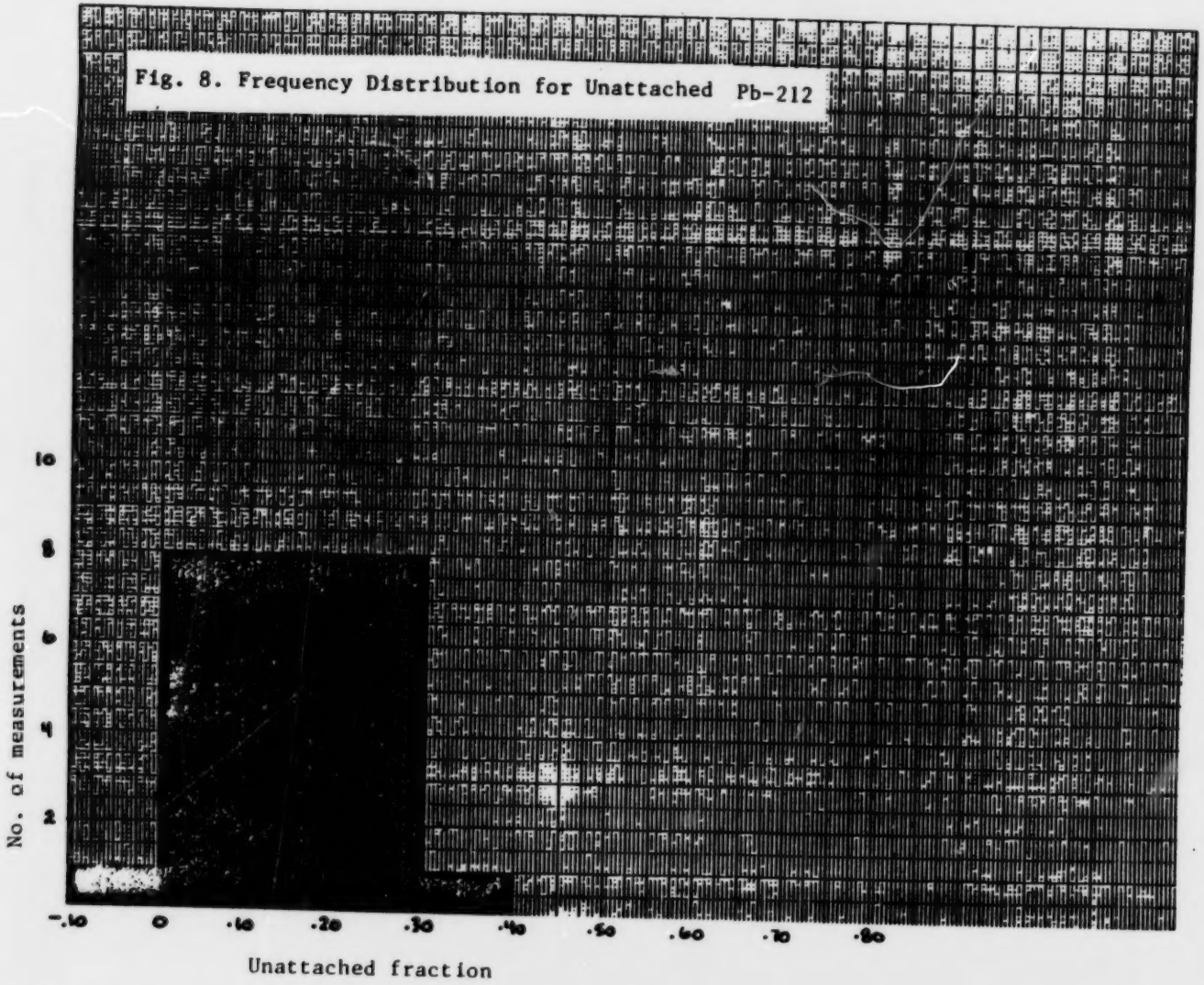


Fig. 8. Frequency Distribution for Unattached Pb-212

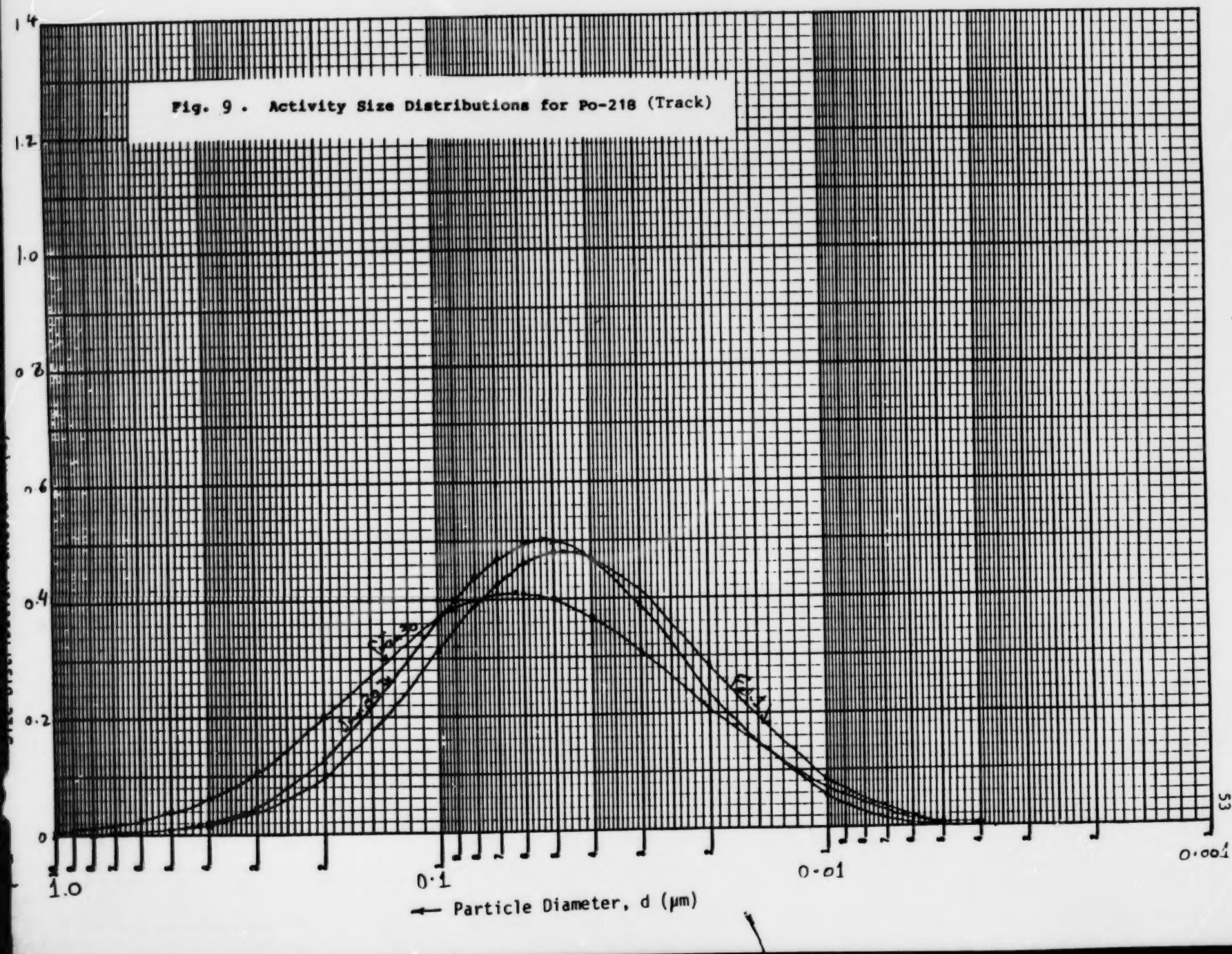


Fig. 9 . Activity Size Distributions for Po-218 (Track)

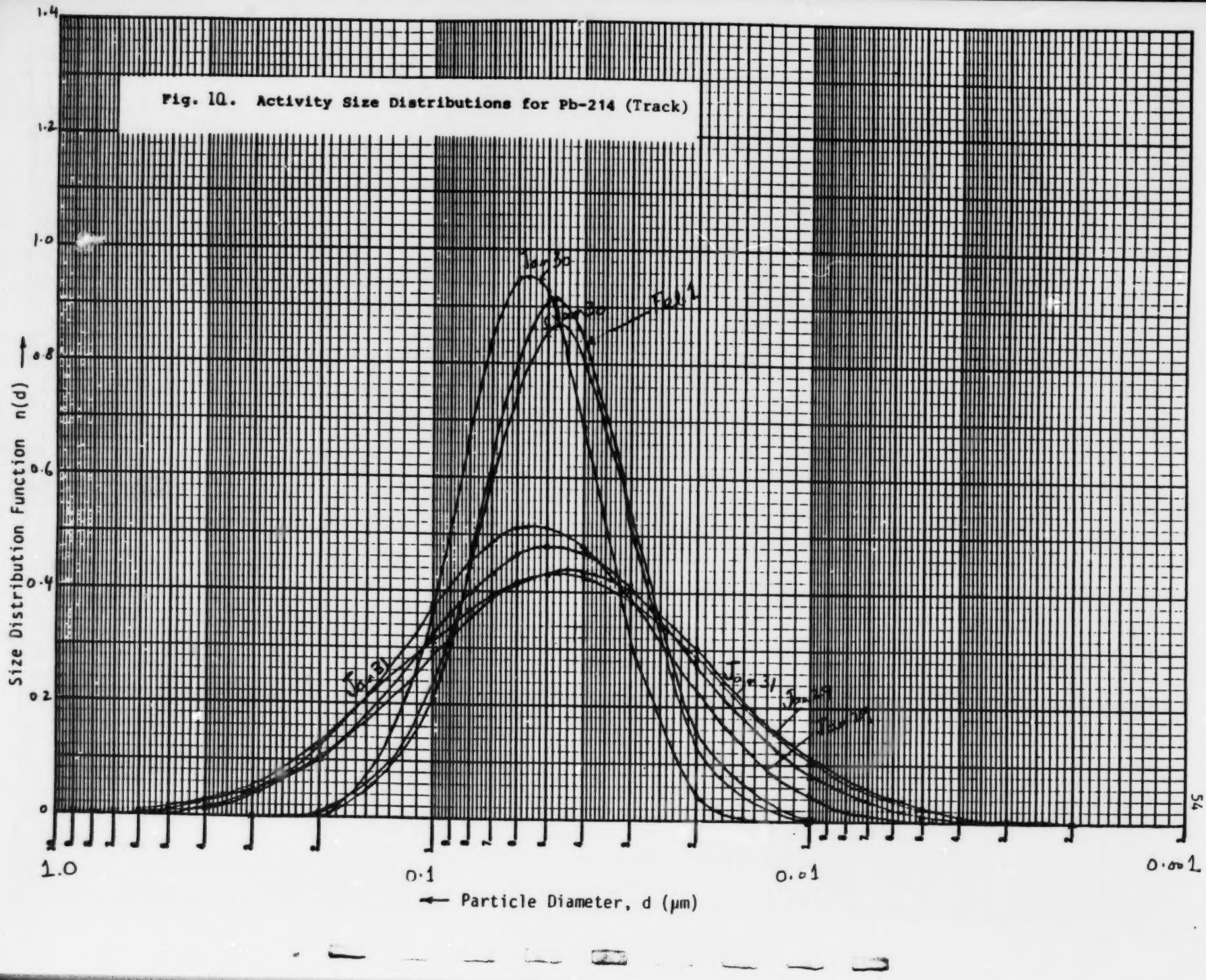


Fig. 10. Activity Size Distributions for Pb-214 (Track)
Size Distribution Function n(d)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1.0
0.1
0.01
0.001
← Particle Diameter, d (μm)

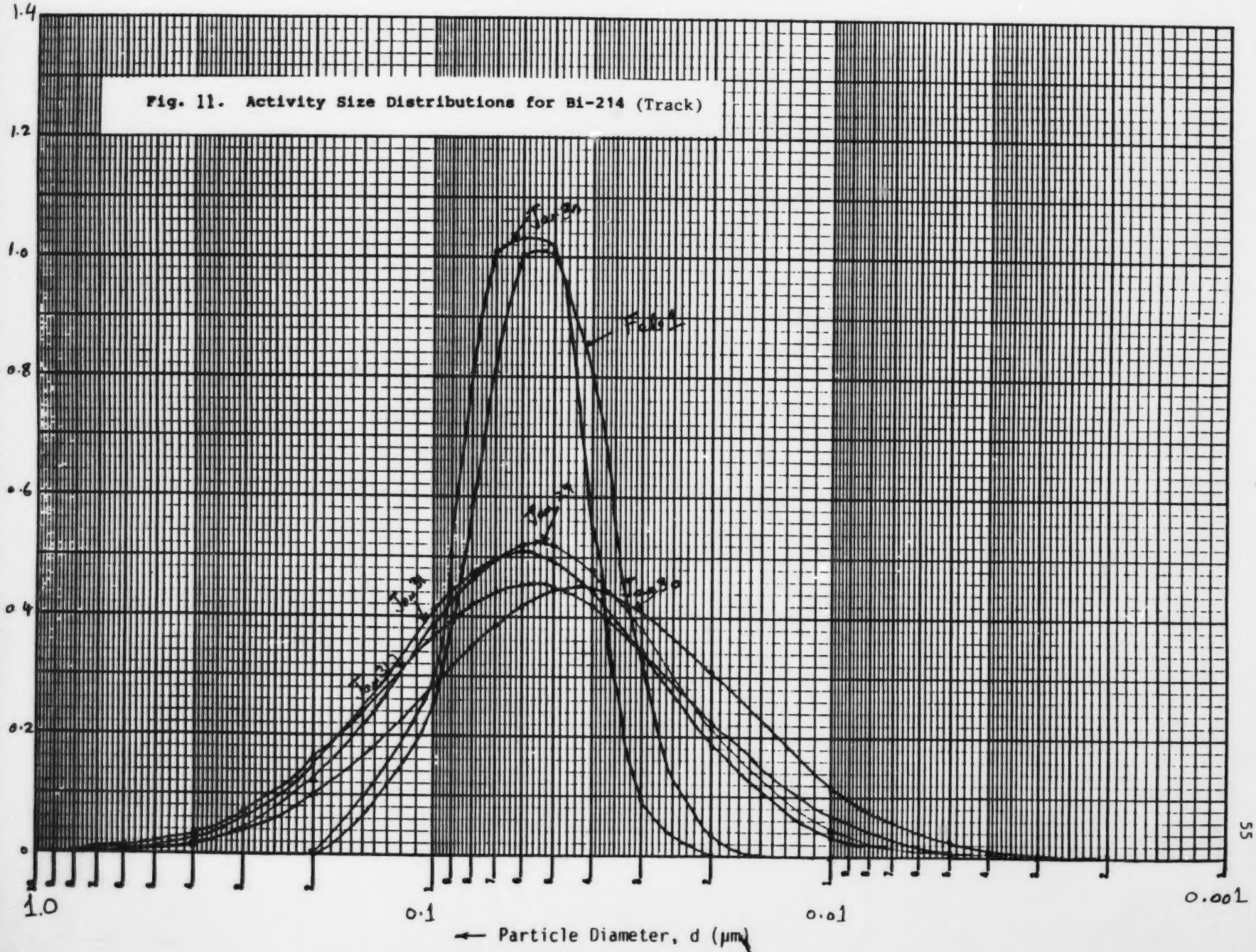


Fig. 11. Activity Size Distributions for Bi-214 (Track)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Size Distribution Function n(d)
1.0
0.1
0.01
0.001
← Particle Diameter, d (μm)

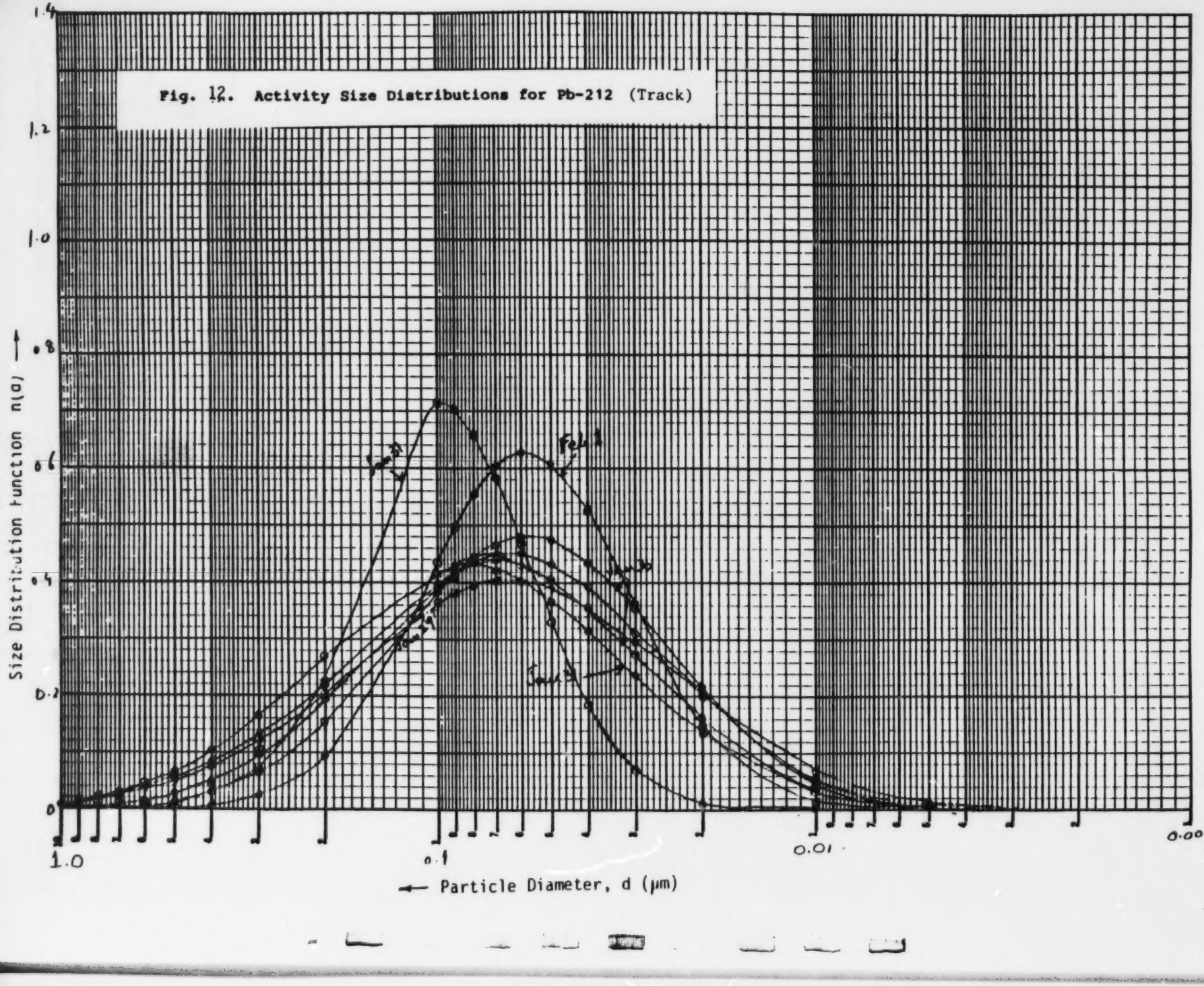


Fig. 12. Activity Size Distributions for Pb-212 (Track)
Size Distribution Function n(a)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1.0
0.1
0.01
0.001
Particle Diameter, d (μm)

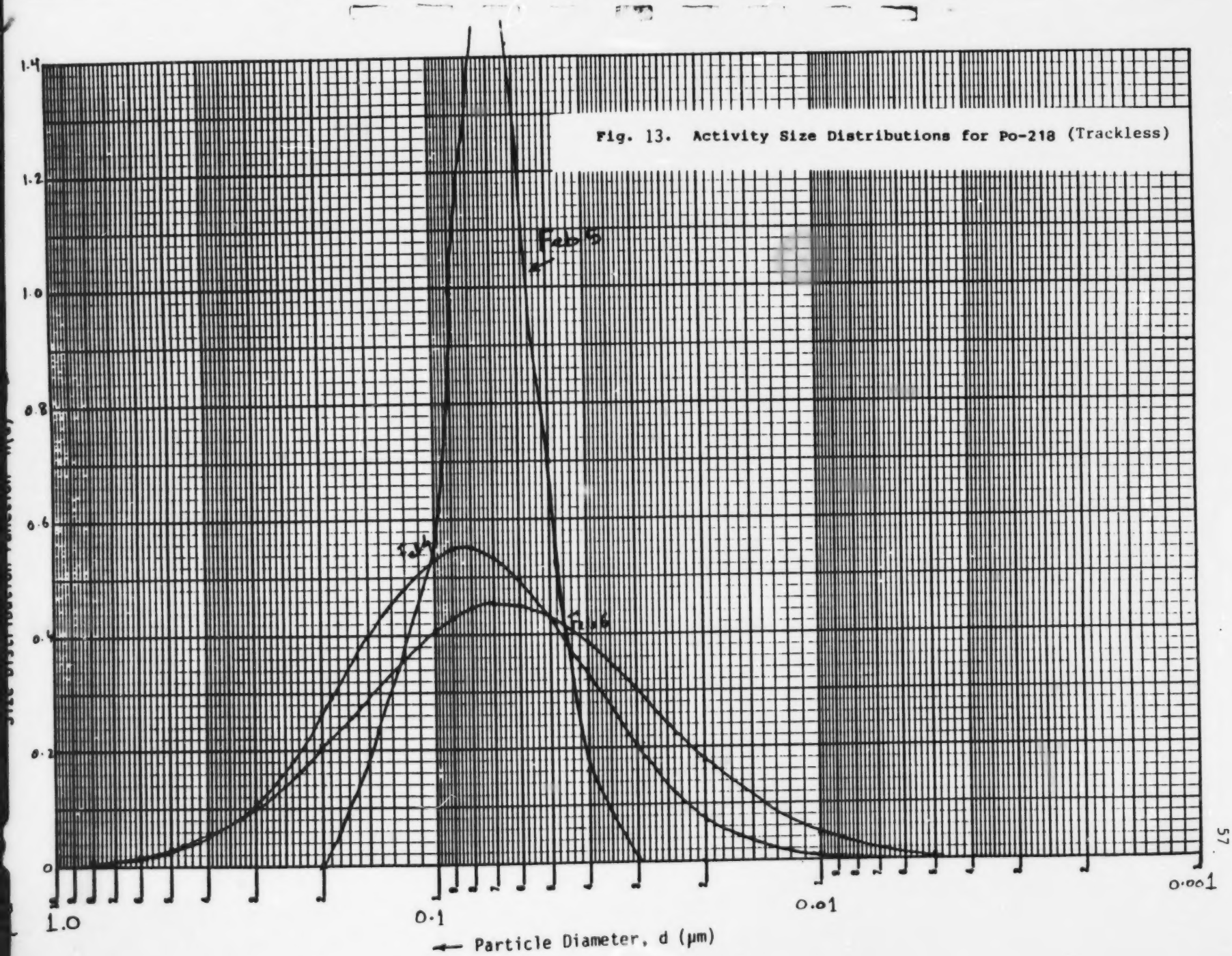


Fig. 13. Activity Size Distributions for Po-218 (Trackless)

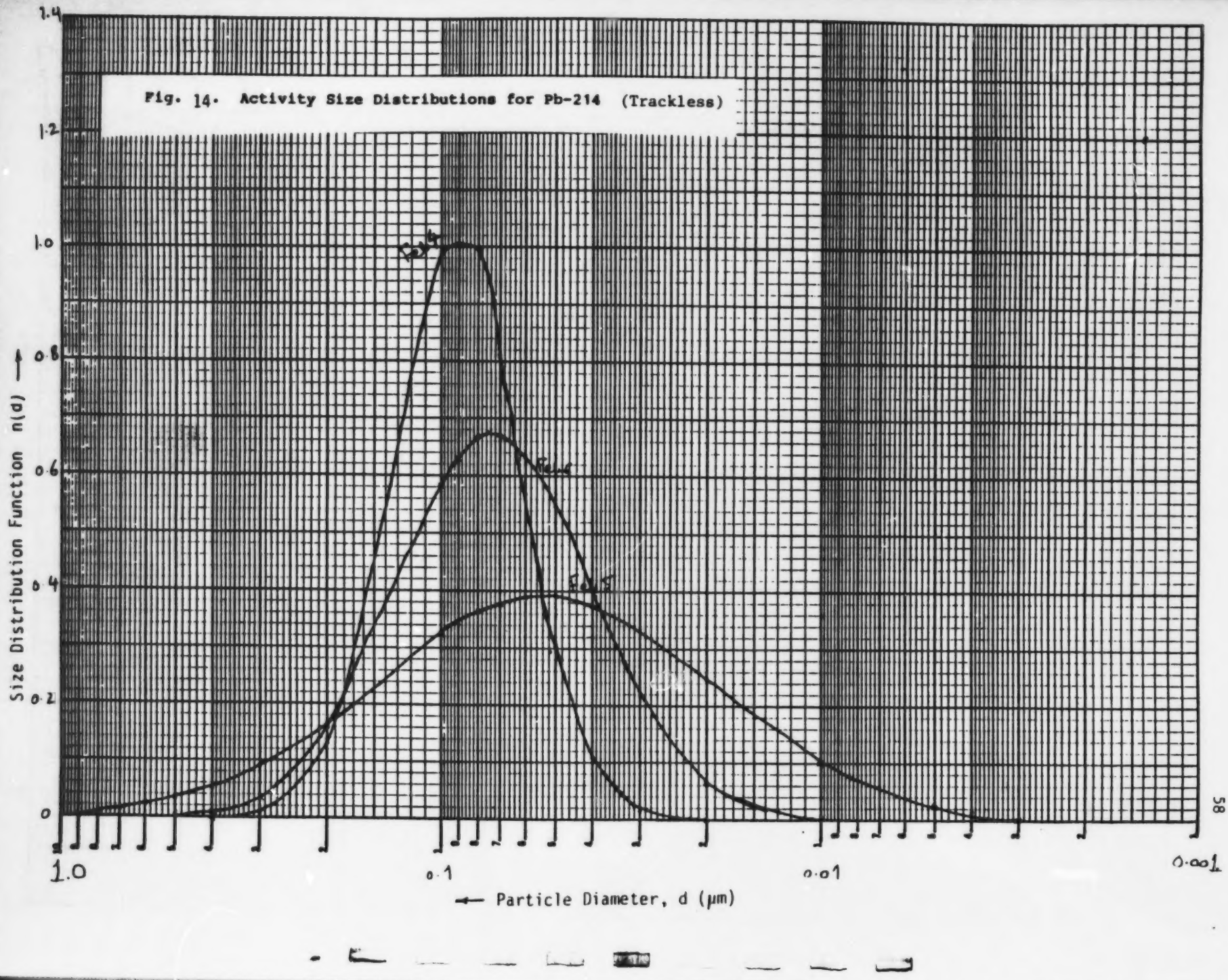


Fig. 14. Activity Size Distributions for Pb-214 (Trackless)

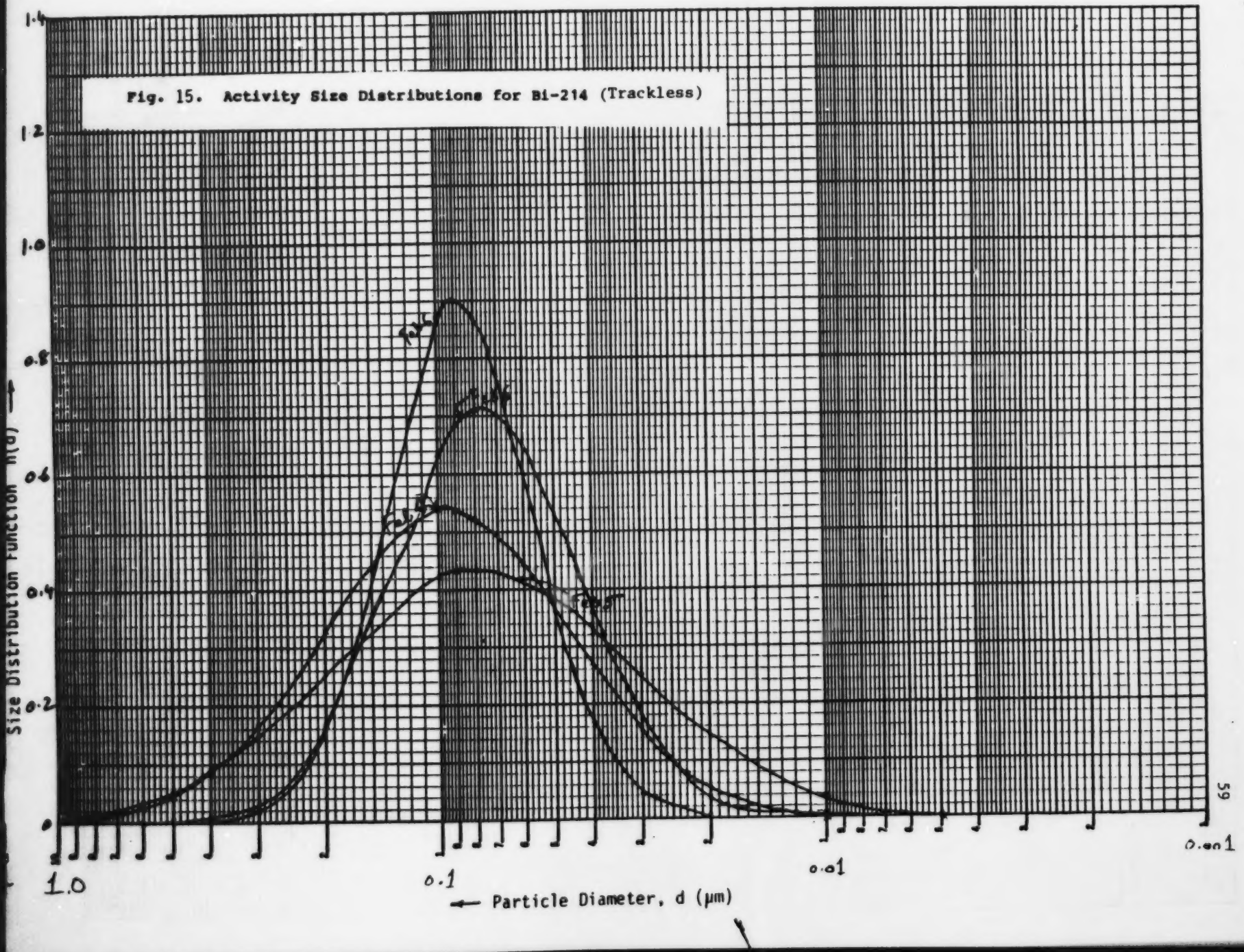


Fig. 15. Activity Size Distributions for Bi-214 (Trackless)

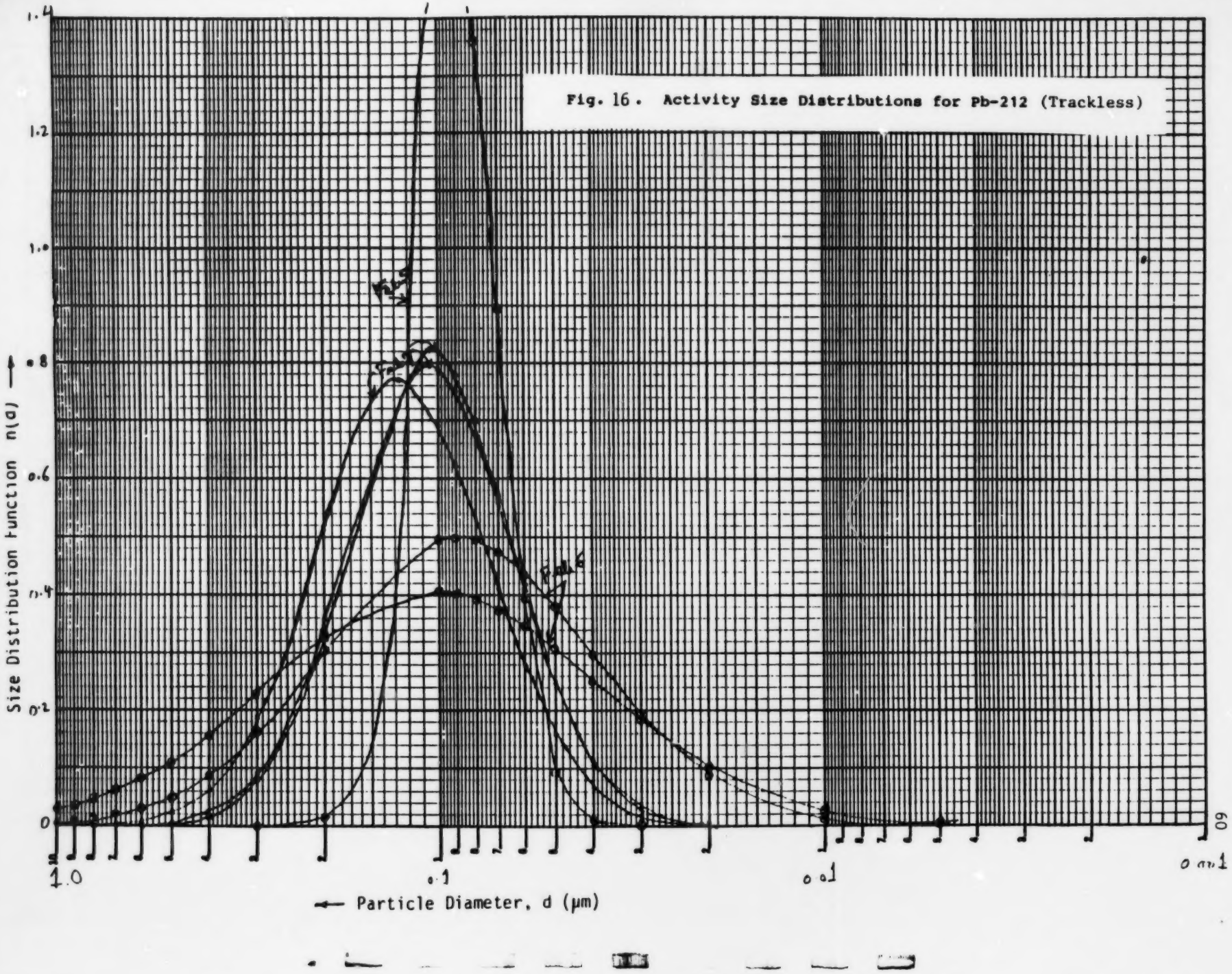


Fig. 16. Activity Size Distributions for Pb-212 (Trackless)

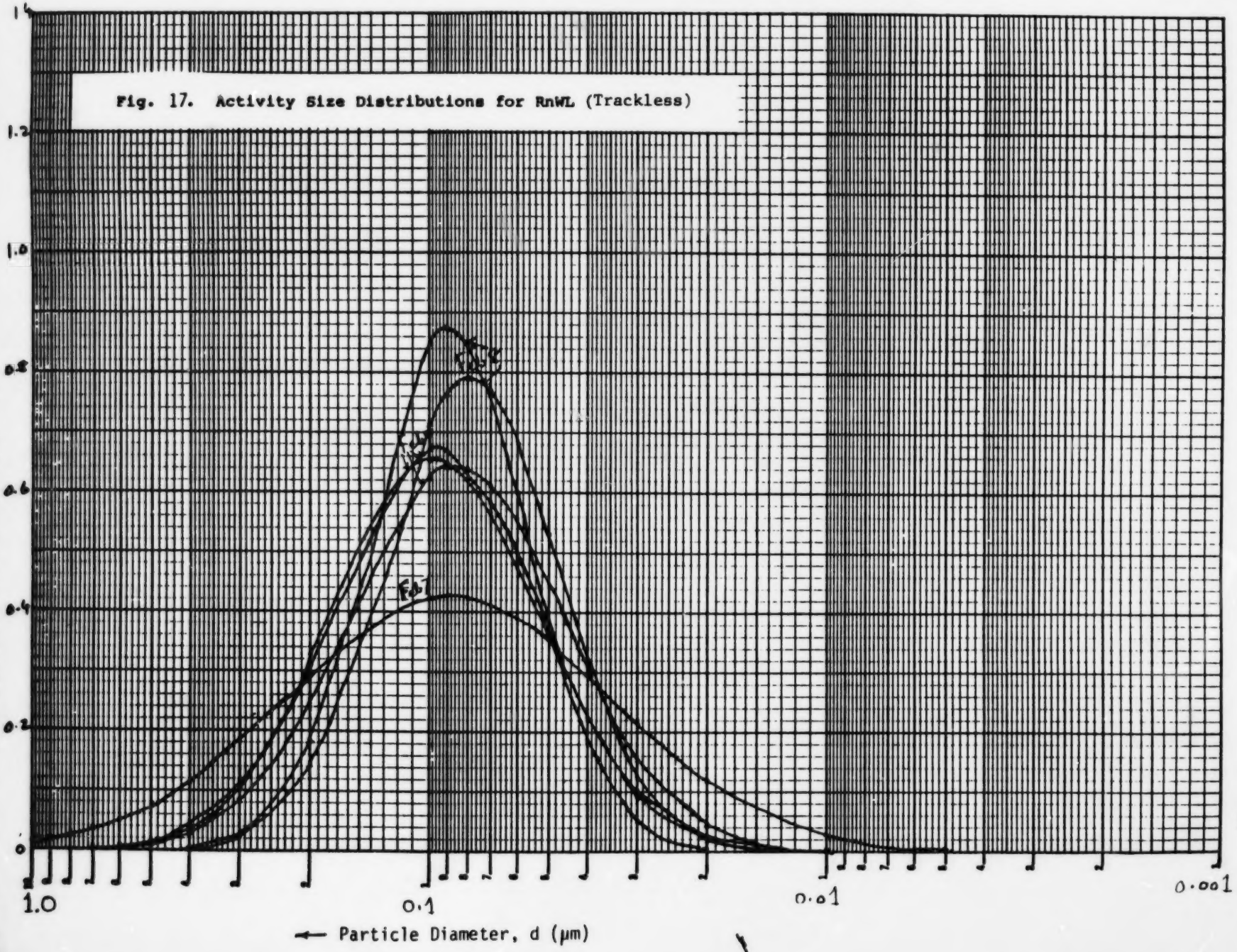


Fig. 17. Activity Size Distributions for RnWL (Trackless)
Size Distribution Function n(d)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1.0
0.1
0.01
0.001
Particle Diameter, d (μm)

FIGURE 18

AEROSOL CONCENTRATIONS FOR JANUARY 30, 1985

AVERAGE TEMPERATURE	=	10.7°C
AVERAGE RELATIVE HUMIDITY	=	85%
AVERAGE VENTILATION RATE	=	14,960 cfm

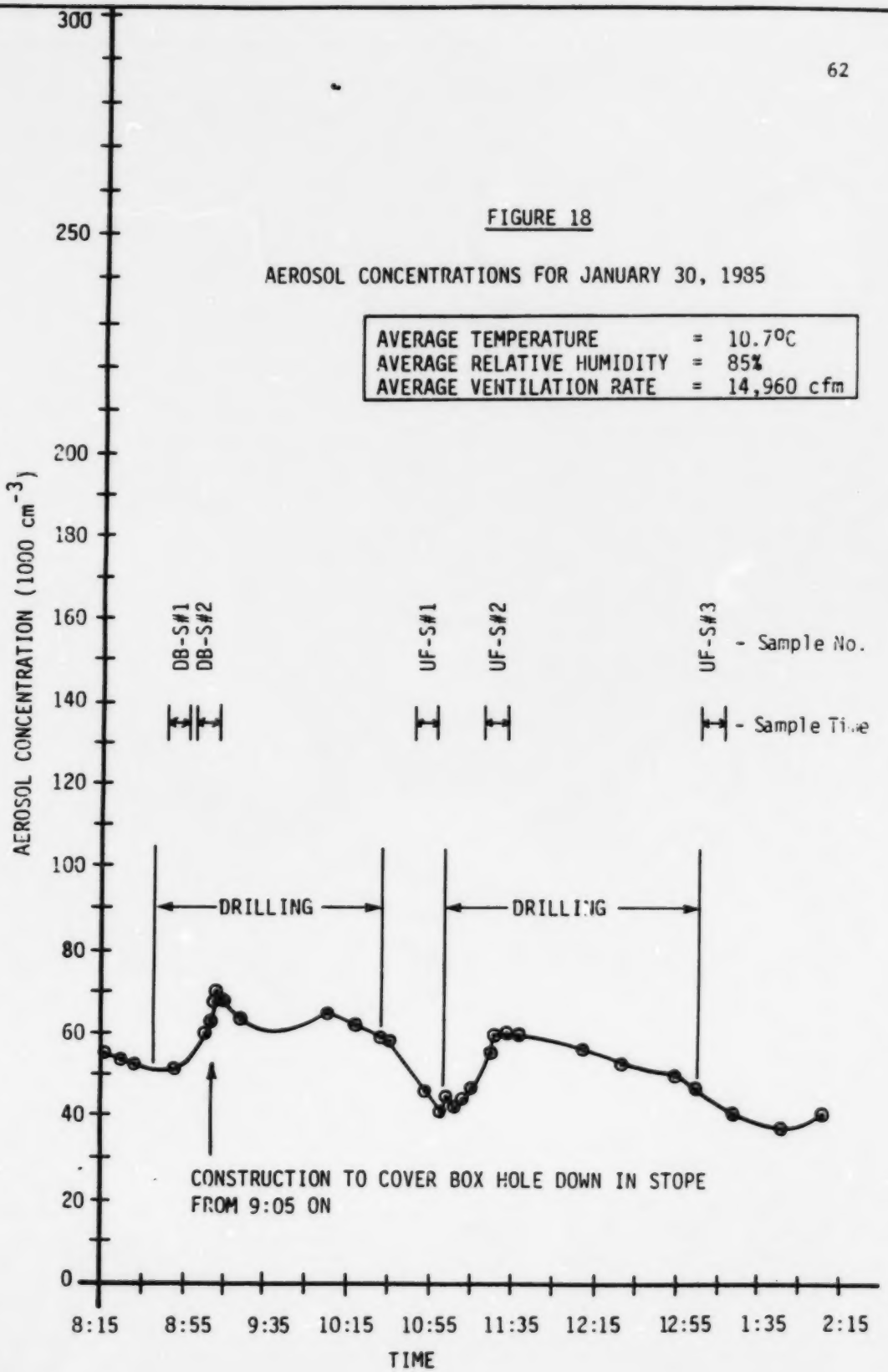


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FIGURE 19

AEROSOL CONCENTRATIONS FOR JANUARY 31, 1985

AVERAGE TEMPERATURE	=	11.2°C
AVERAGE RELATIVE HUMIDITY	=	86%
AVERAGE VENTILATION RATE	=	9,150 cfm

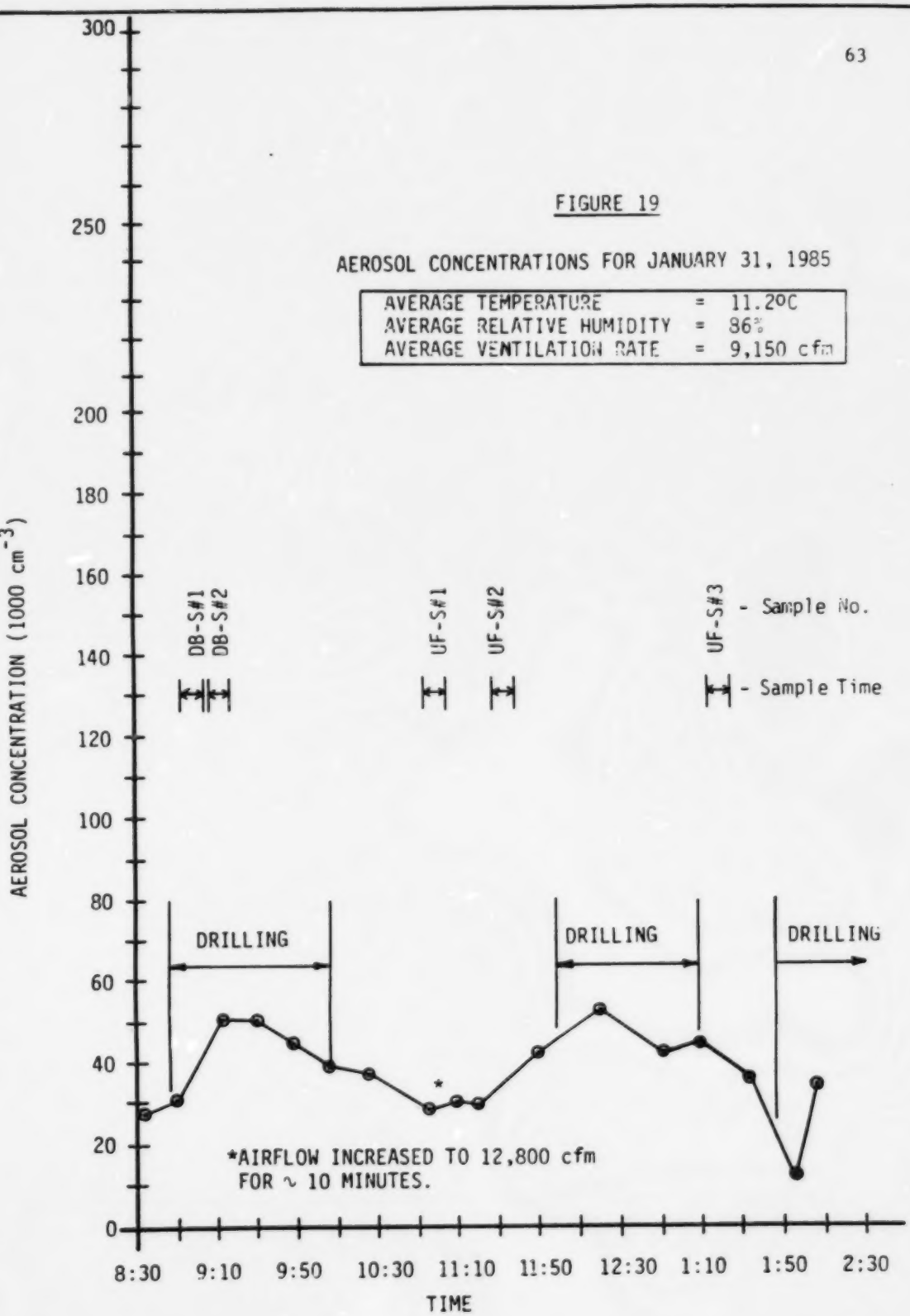

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FIGURE 20

AEROSOL CONCENTRATIONS FOR FEBRUARY 1, 1985

AVERAGE TEMPERATURE	=	11.3°C
AVERAGE RELATIVE HUMIDITY	=	67%
AVERAGE VENTILATION RATE	=	16,500 cfm

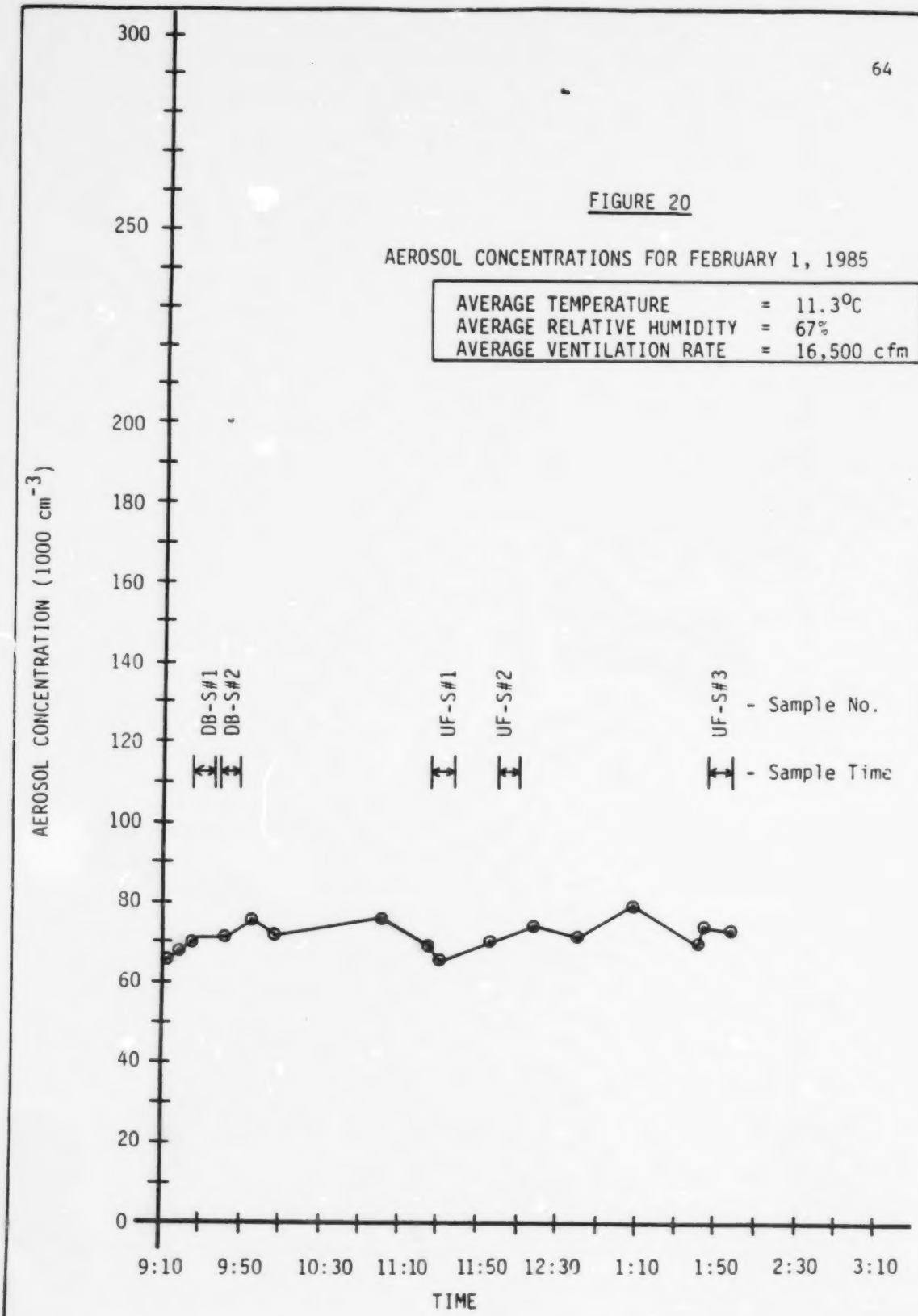

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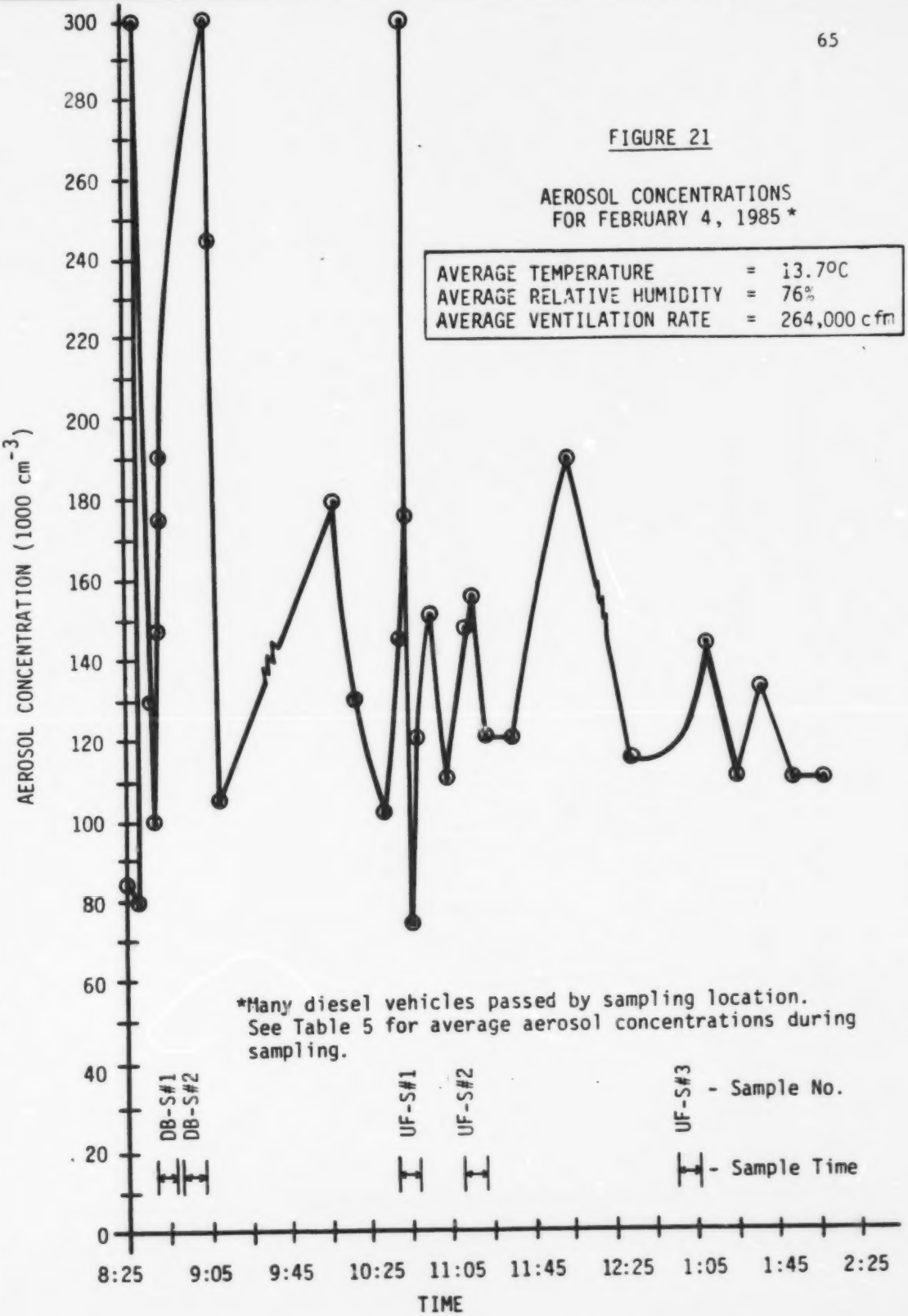
FIGURE 21

AEROSOL CONCENTRATIONS
FOR FEBRUARY 4, 1985 *

AVERAGE TEMPERATURE	=	13.7°C
AVERAGE RELATIVE HUMIDITY	=	76%
AVERAGE VENTILATION RATE	=	264,000 cfm



*Many diesel vehicles passed by sampling location. See Table 5 for average aerosol concentrations during sampling.

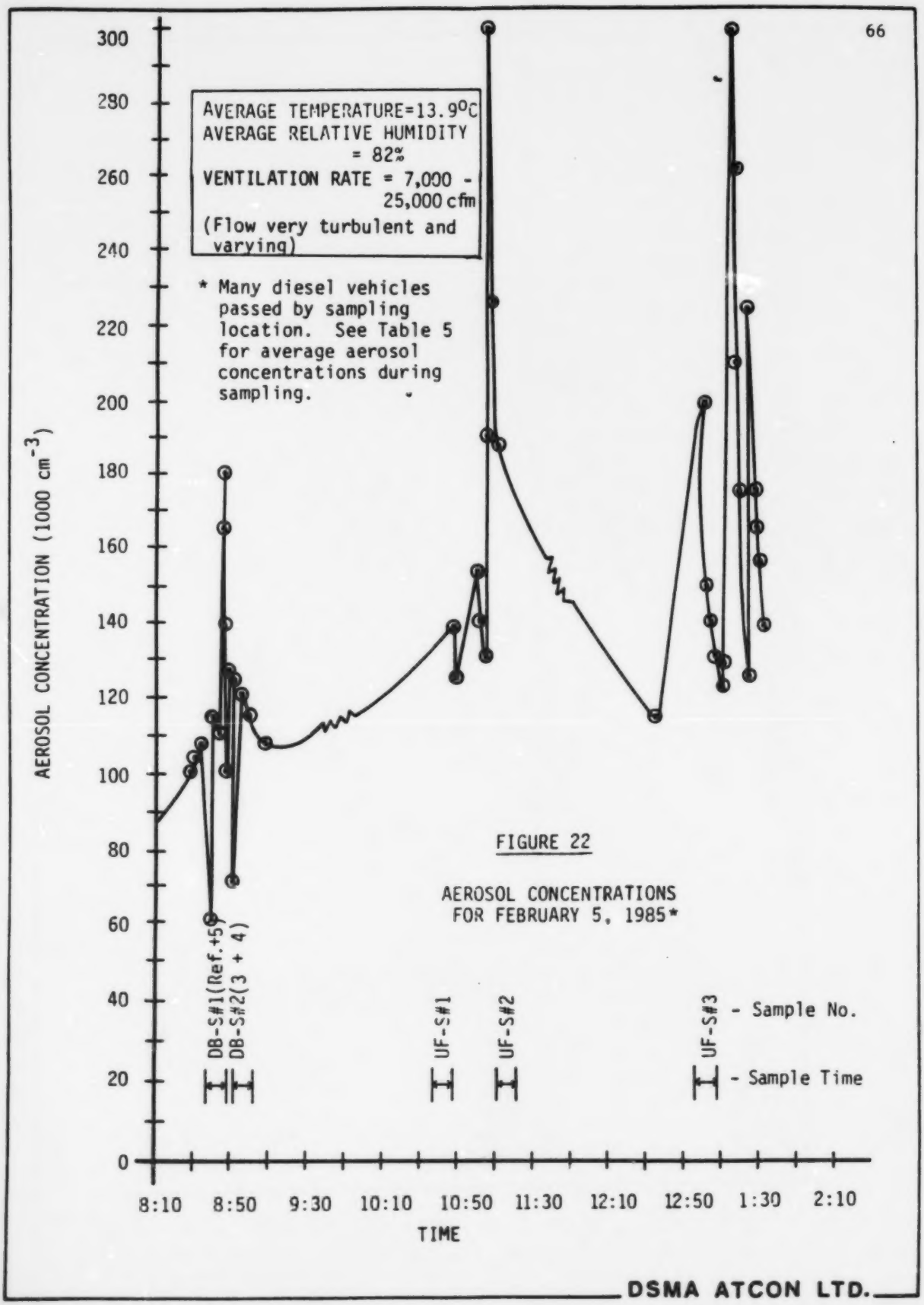


FIGURE 22

AEROSOL CONCENTRATIONS FOR FEBRUARY 5, 1985*

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FIGURE 23

AEROSOL CONCENTRATIONS FOR FEBRUARY 6, 1985

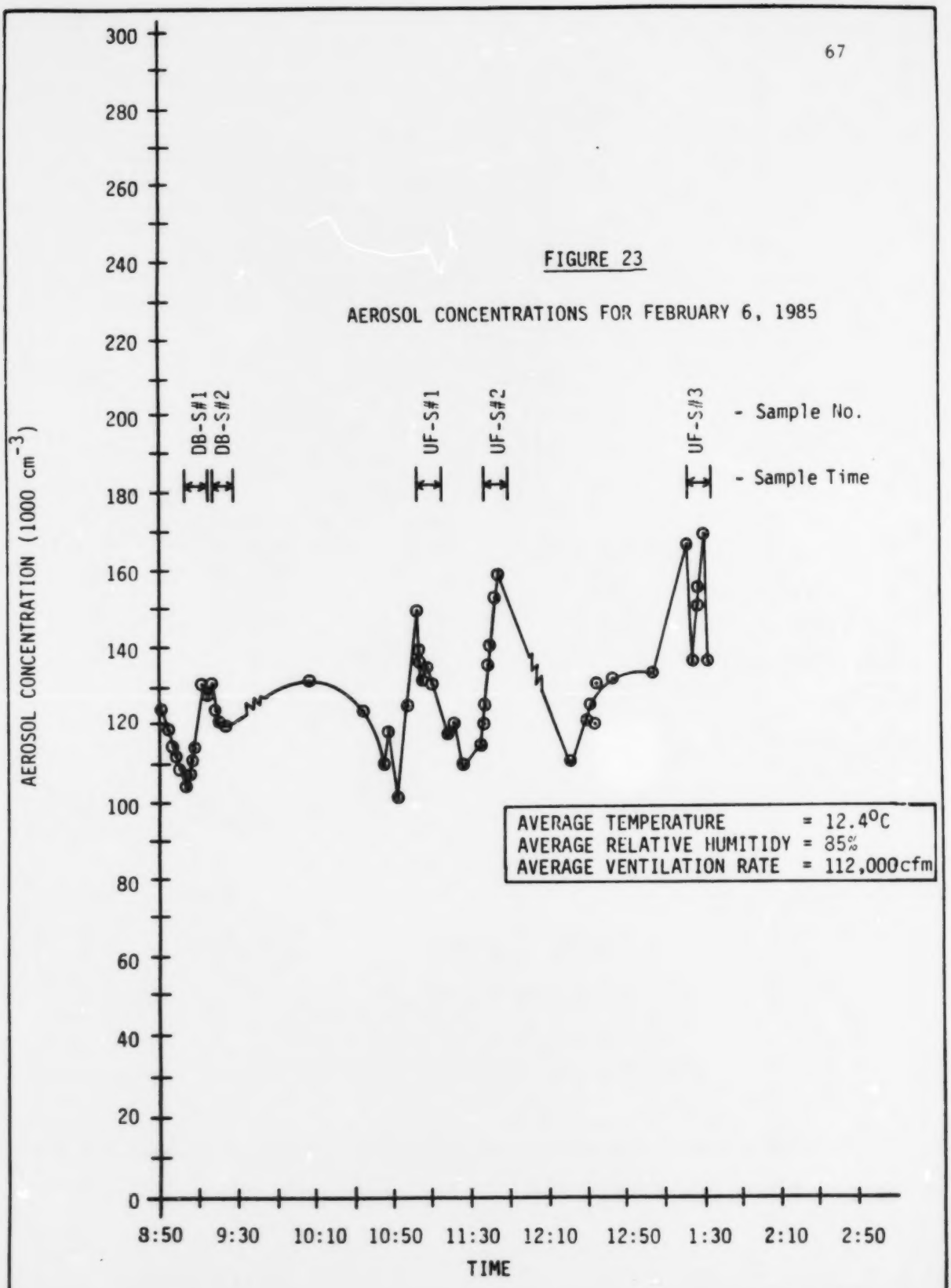

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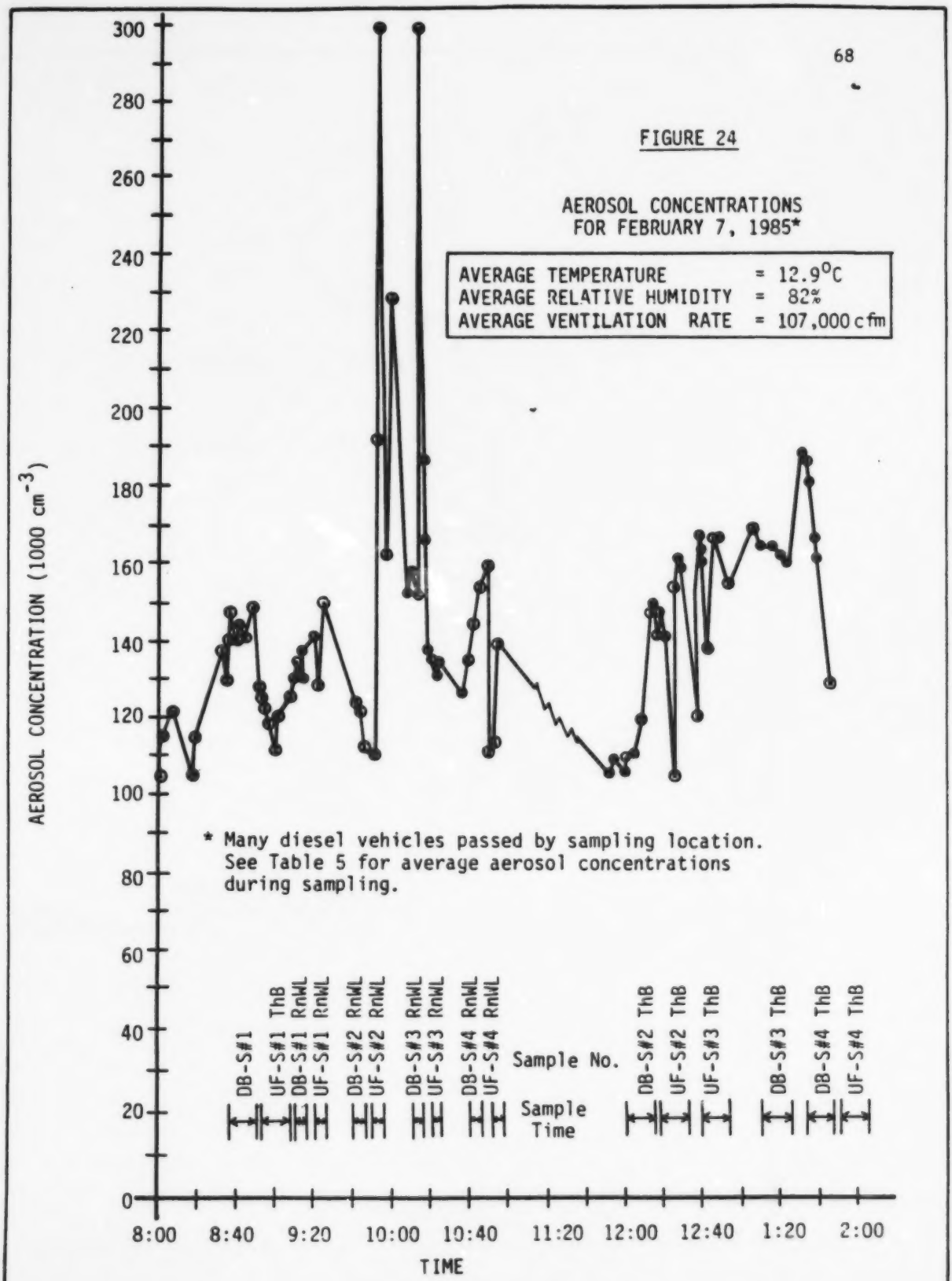
FIGURE 24

AEROSOL CONCENTRATIONS
FOR FEBRUARY 7, 1985*

AVERAGE TEMPERATURE	= 12.9°C
AVERAGE RELATIVE HUMIDITY	= 82%
AVERAGE VENTILATION RATE	= 107,000 cfm



* Many diesel vehicles passed by sampling location. See Table 5 for average aerosol concentrations during sampling.

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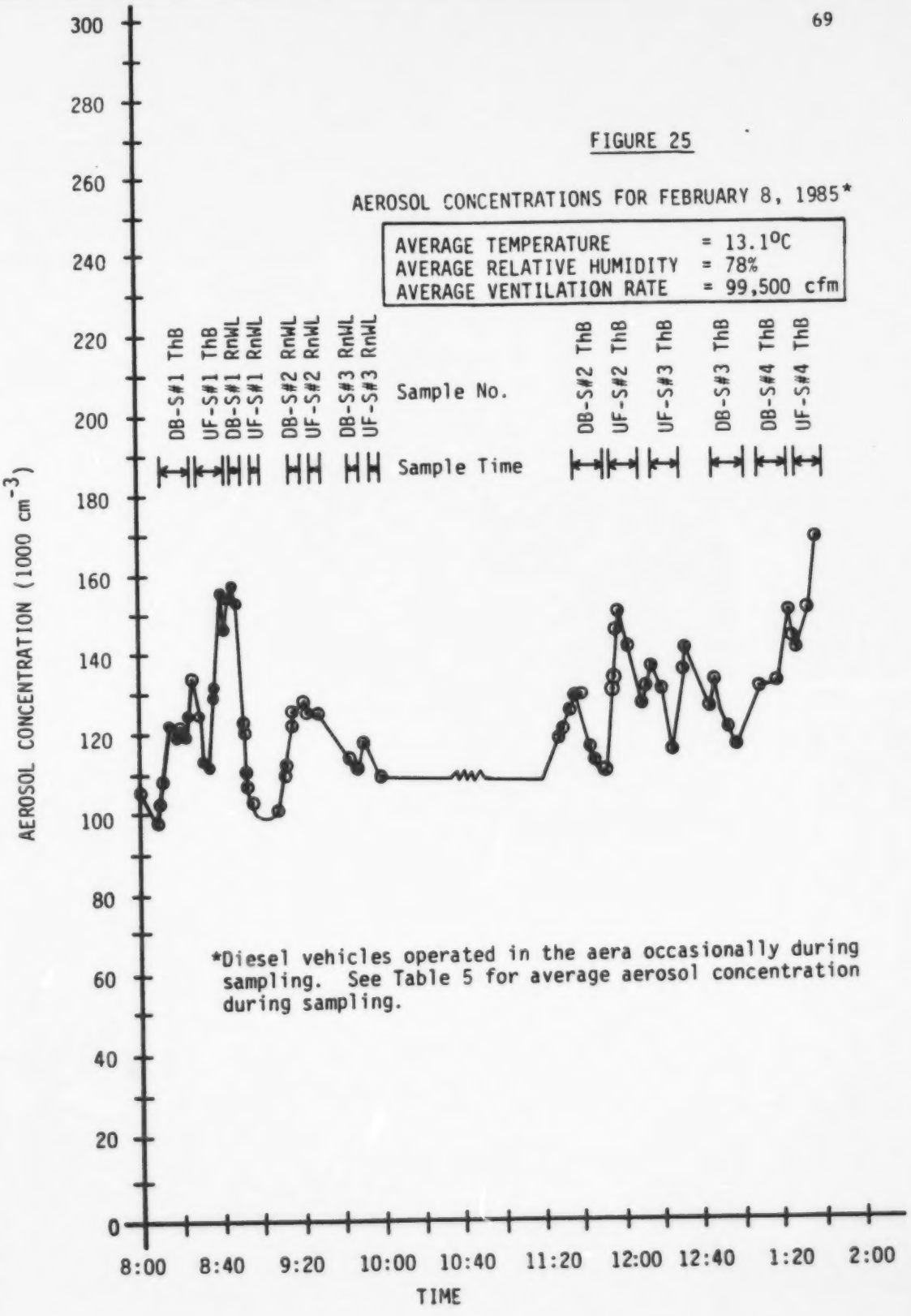
FIGURE 25

AEROSOL CONCENTRATIONS FOR FEBRUARY 8, 1985*

AVERAGE TEMPERATURE	= 13.1°C
AVERAGE RELATIVE HUMIDITY	= 78%
AVERAGE VENTILATION RATE	= 99,500 cfm



*Diesel vehicles operated in the aera occasionally during sampling. See Table 5 for average aerosol concentration during sampling.

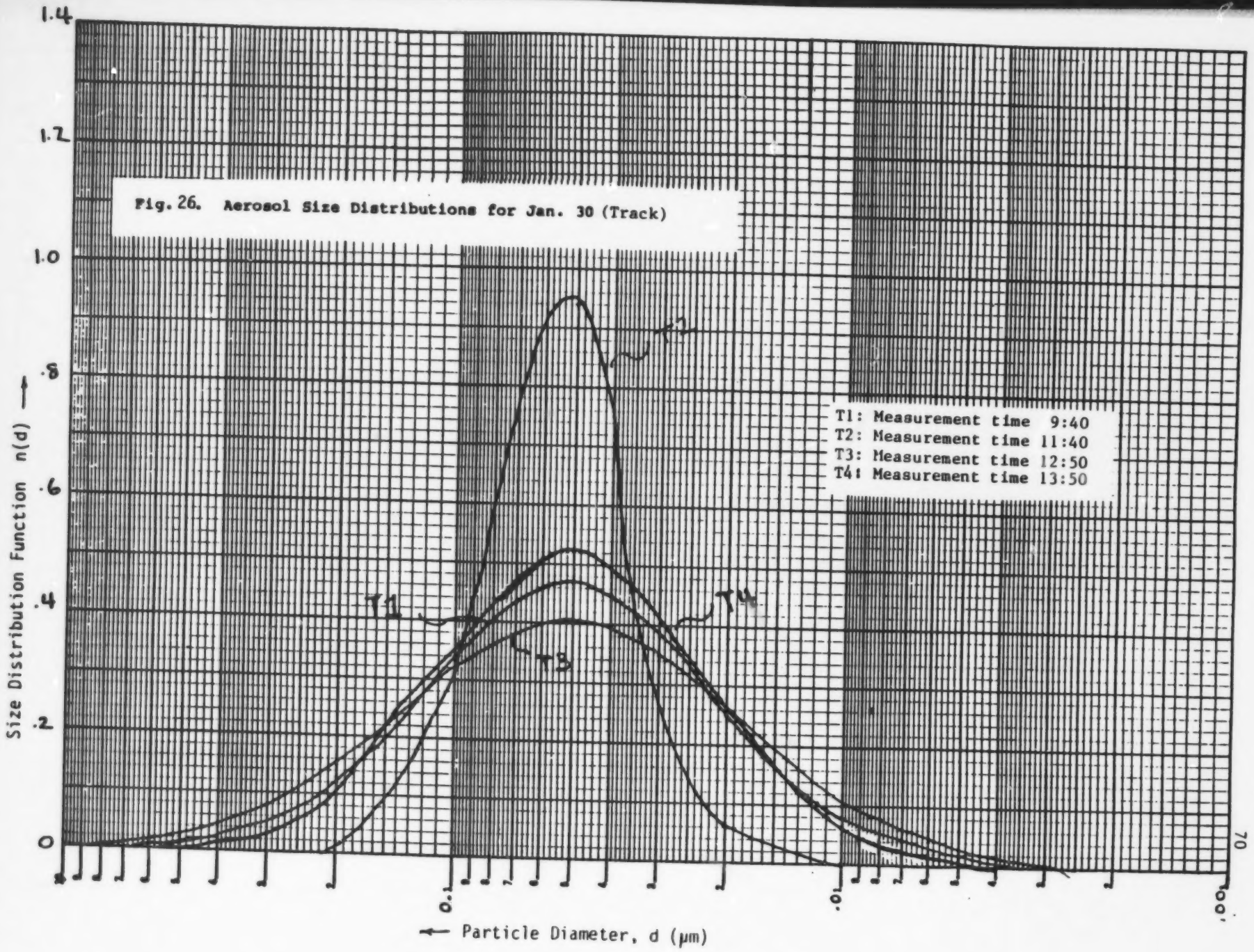


Fig. 26. Aerosol Size Distributions for Jan. 30 (Track)
T1: Measurement time 9:40
T2: Measurement time 11:40
T3: Measurement time 12:50
T4: Measurement time 13:50
T1
T2
T3
T4
Size Distribution Function n(d) →
1.4
1.2
1.0
.8
.6
.4
.2
0
0.1
0.0
.00
70
← Particle Diameter, d (μm)

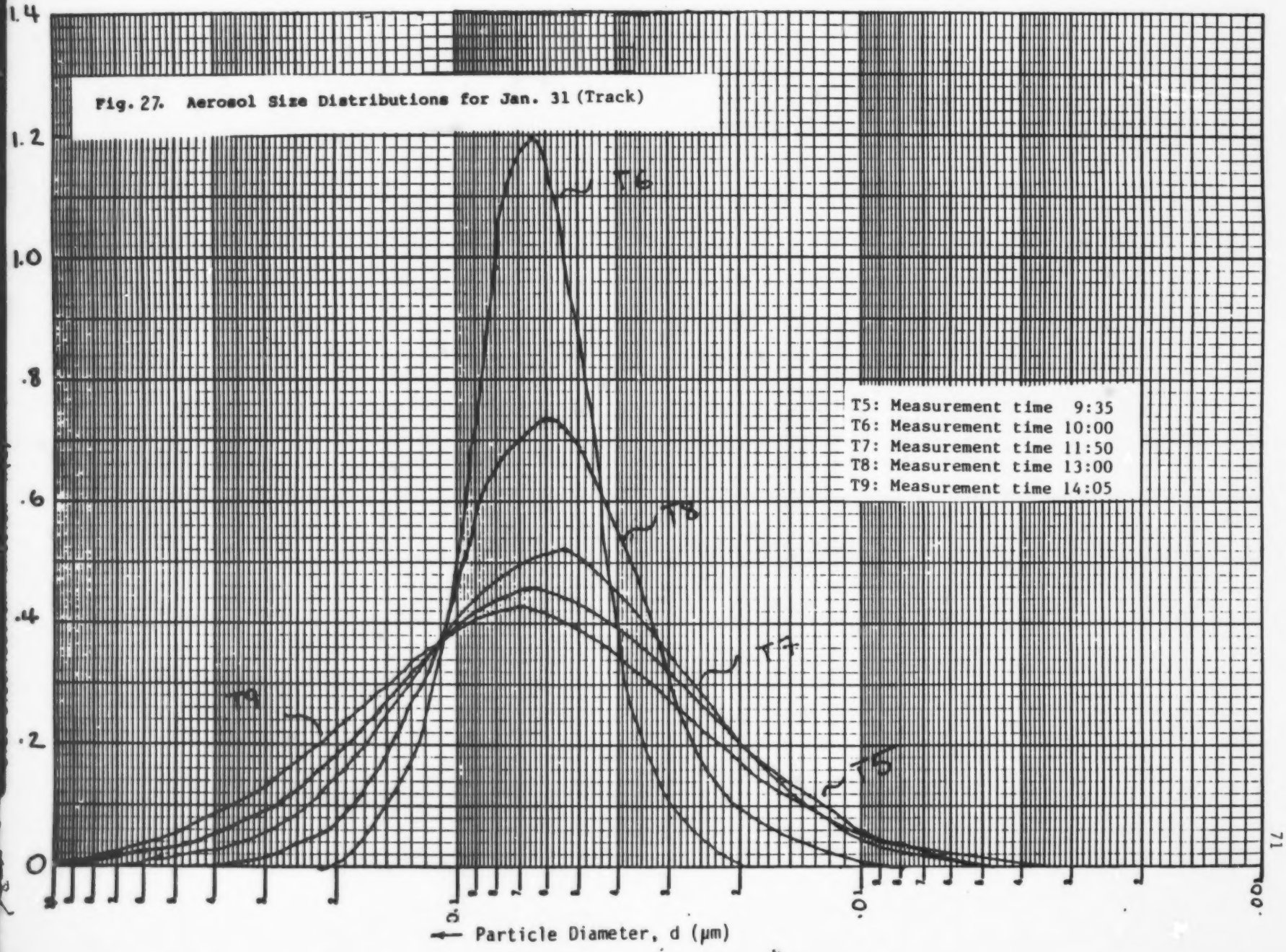


Fig. 27. Aerosol Size Distributions for Jan. 31 (Track)
T5: Measurement time 9:35
T6: Measurement time 10:00
T7: Measurement time 11:50
T8: Measurement time 13:00
T9: Measurement time 14:05
T6
T8
T7
T5
T9
1.4
1.2
1.0
.8
.6
.4
.2
0
.01
.1
1.0
100
Particle Diameter, d (μm)

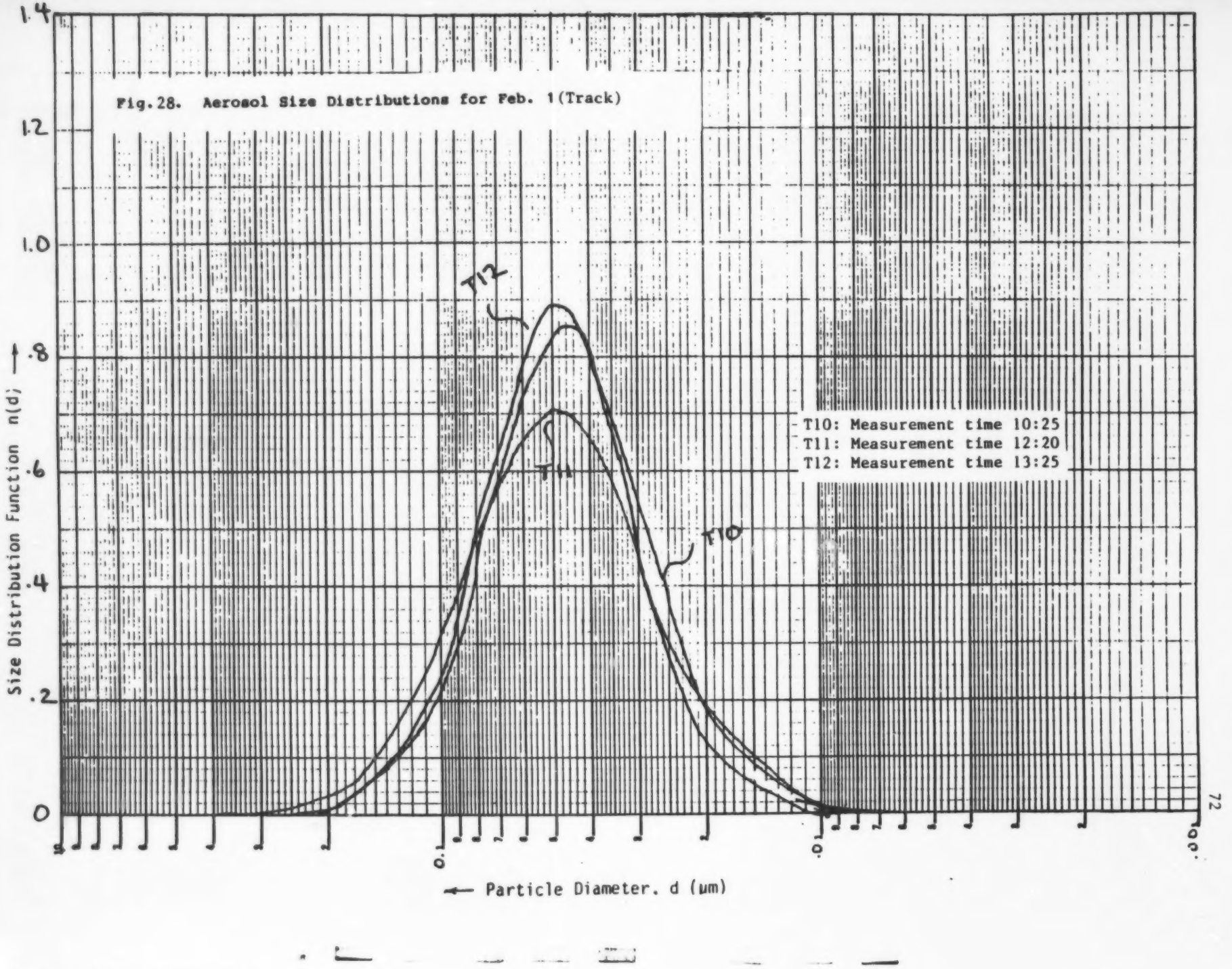


Fig. 28. Aerosol Size Distributions for Feb. 1 (Track)
1.4
1.2
1.0
.8
.6
.4
.2
0
Size Distribution Function n(d) →
T12
T11
T10
T10: Measurement time 10:25
T11: Measurement time 12:20
T12: Measurement time 13:25
0.1
1.0
10.0
← Particle Diameter, d (μm)

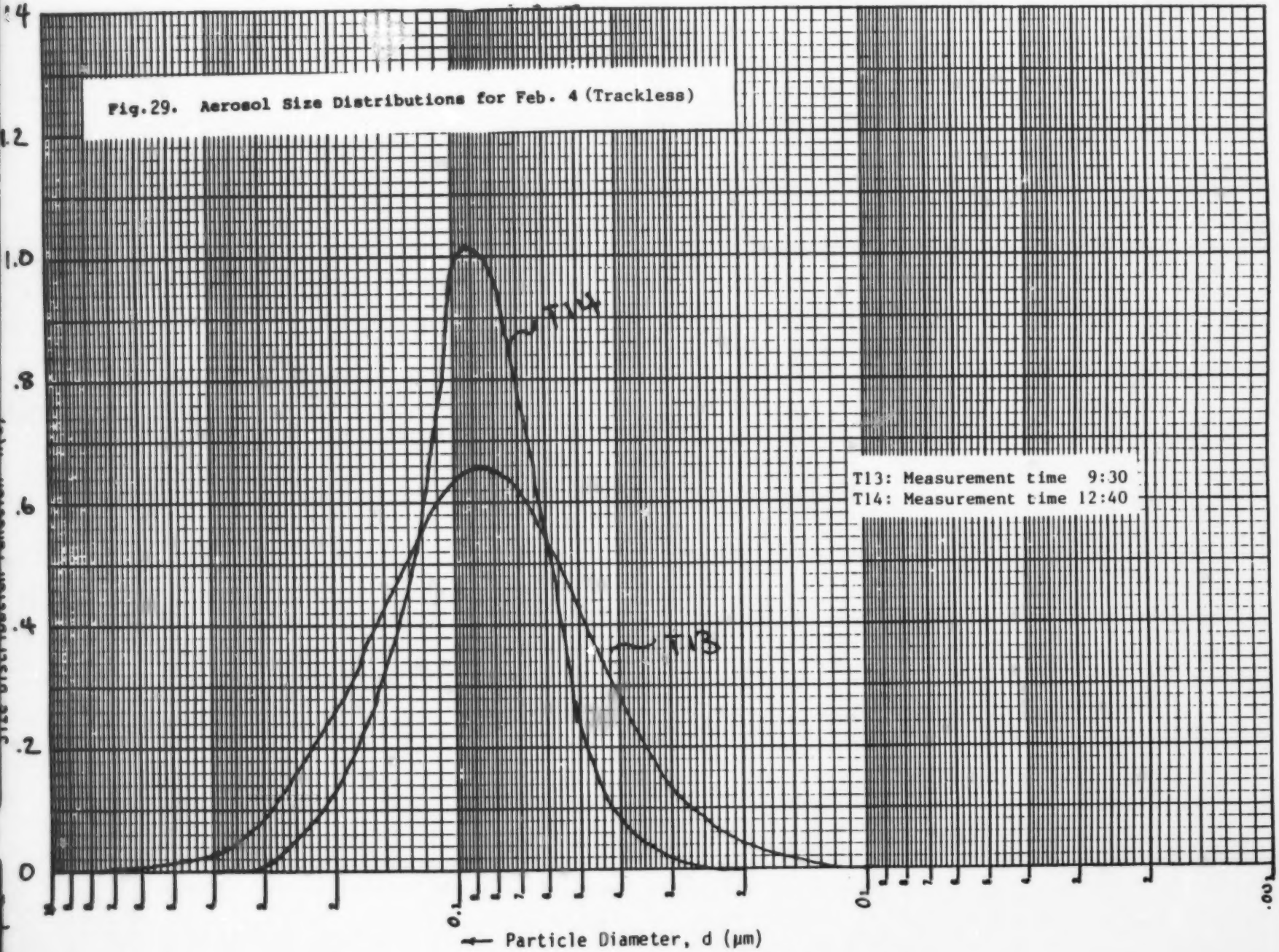


Fig.29. Aerosol Size Distributions for Feb. 4 (Trackless)
T13: Measurement time 9:30
T14: Measurement time 12:40
T14
T13
1.4
1.2
1.0
.8
.6
.4
.2
0
0.1
1.0
100
← Particle Diameter, d (μm)

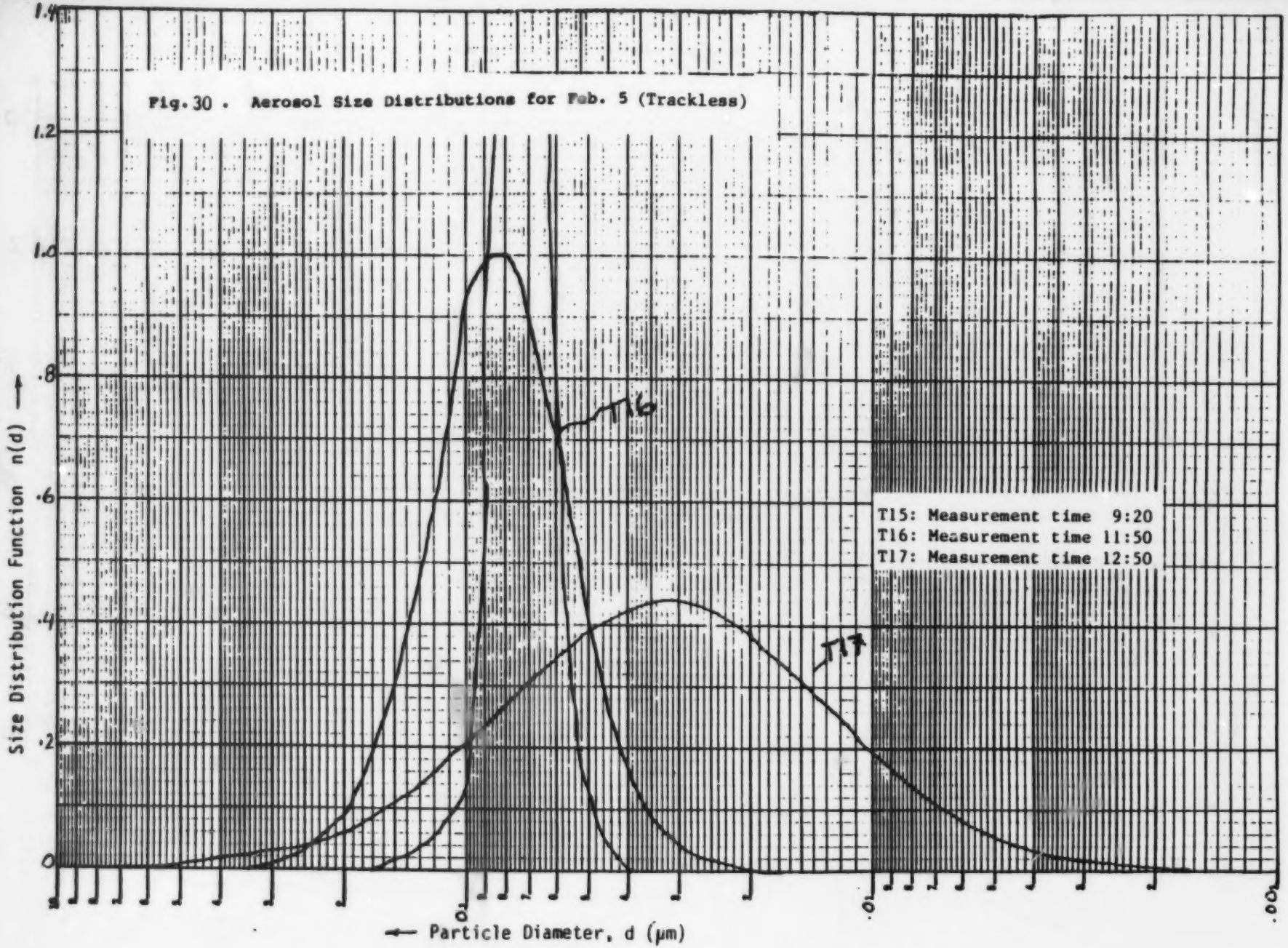


Fig. 30 . Aerosol Size Distributions for Feb. 5 (Trackless)
Size Distribution Function n(d) →
1.4
1.2
1.0
.8
.6
.4
.2
0
T16
T17
T15: Measurement time 9:20
T16: Measurement time 11:50
T17: Measurement time 12:50
← Particle Diameter, d (μm)

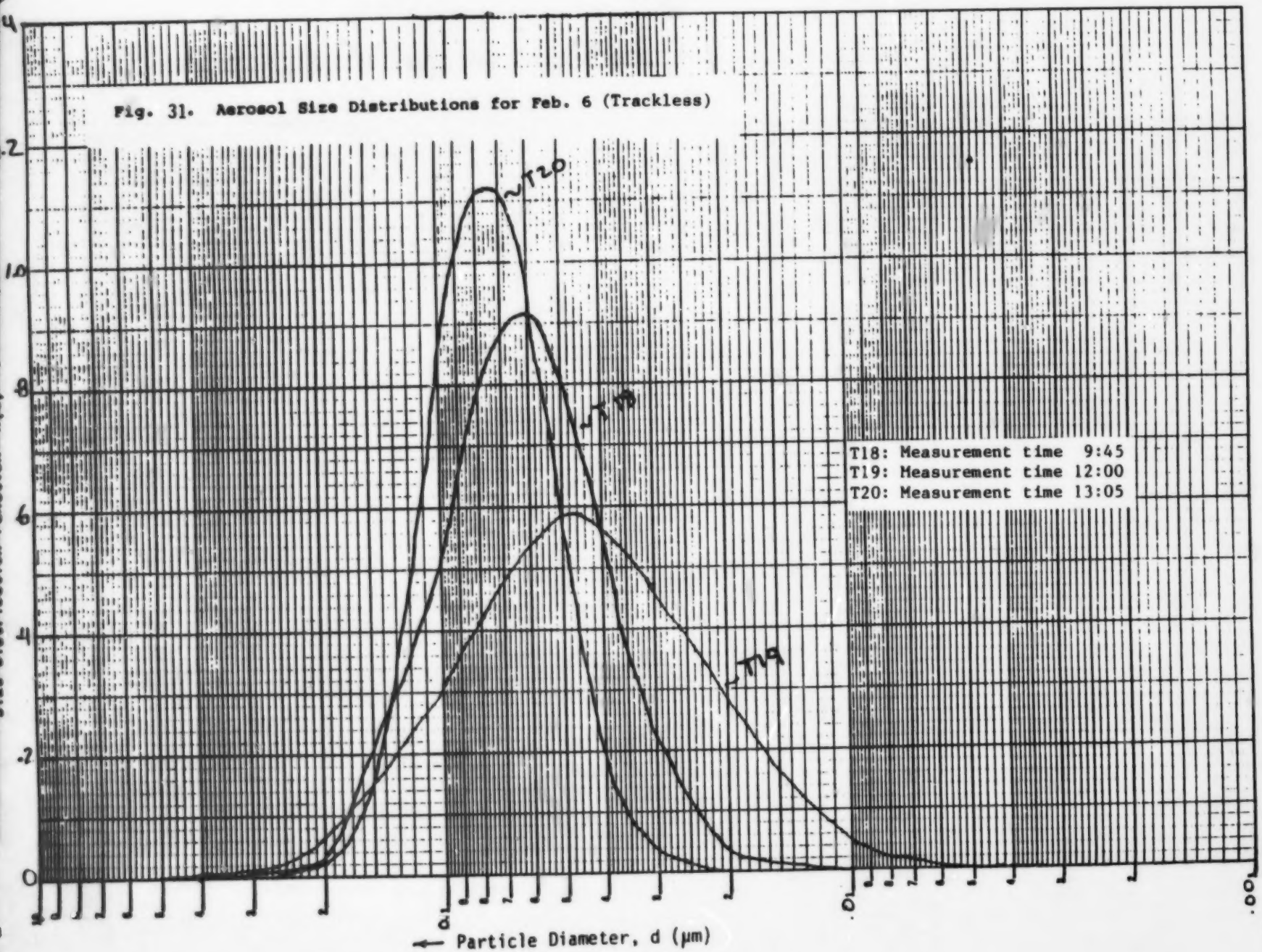


Fig. 31. Aerosol Size Distributions for Feb. 6 (Trackless)
T20
T18
T19
T18: Measurement time 9:45
T19: Measurement time 12:00
T20: Measurement time 13:05
Particle Diameter, d (μm)

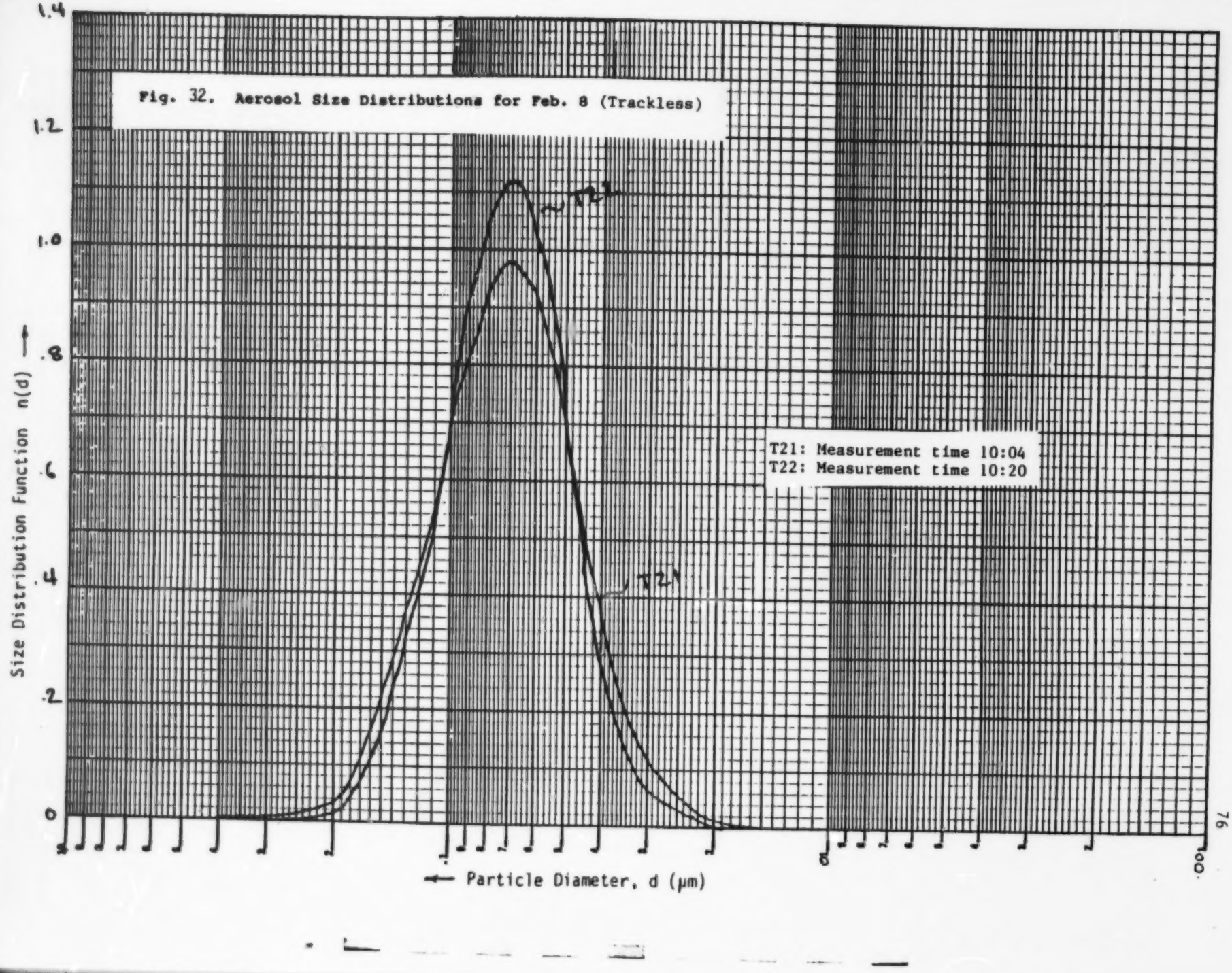


Fig. 32. Aerosol Size Distributions for Feb. 8 (Trackless)
T21: Measurement time 10:04
T22: Measurement time 10:20
T21
T22
Size Distribution Function n(d)
Particle Diameter, d (μm)
1.4
1.2
1.0
.8
.6
.4
.2
0
6
100

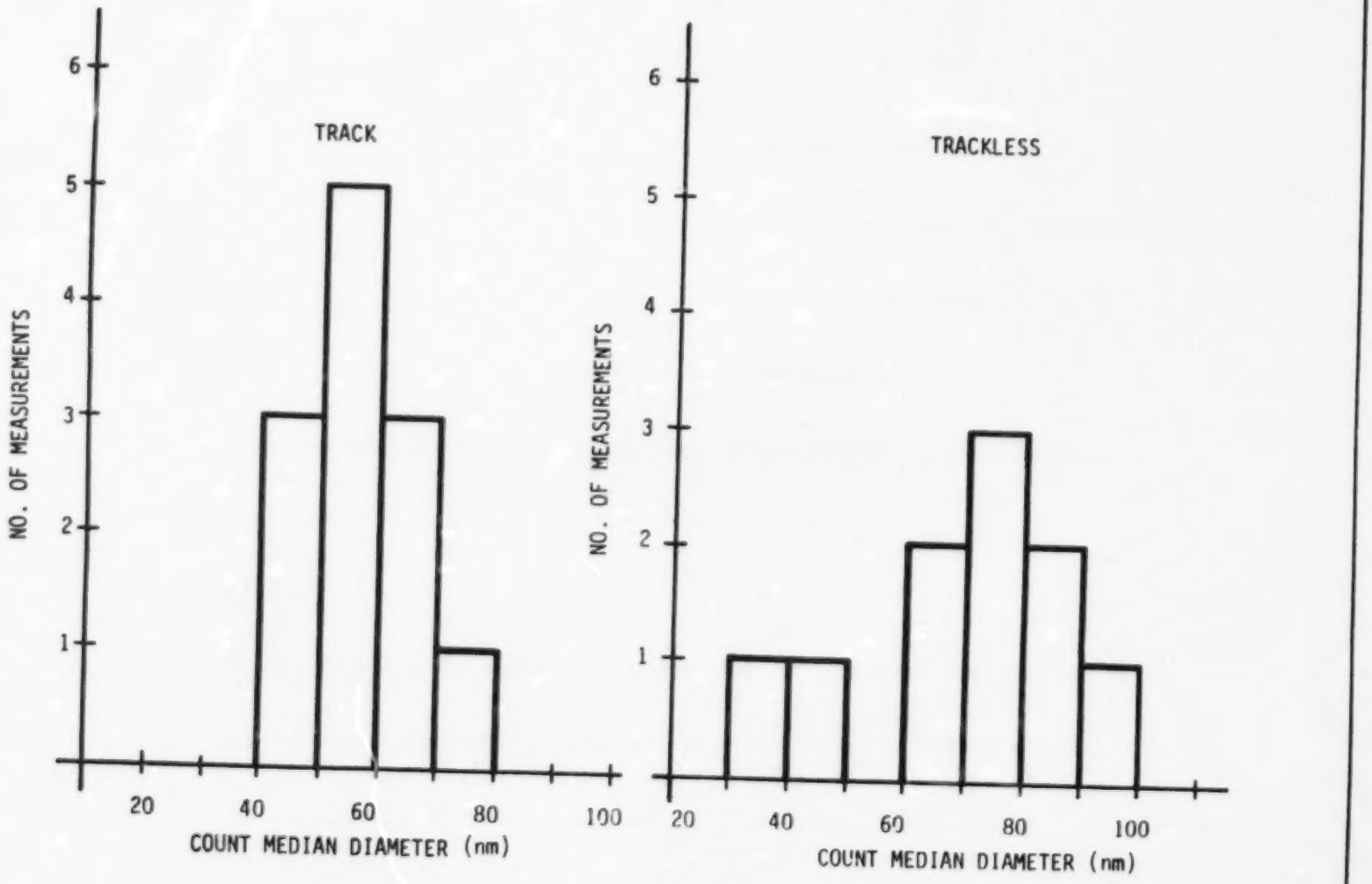


FIGURE 33

FREQUENCY DISTRIBUTIONS FOR PARTICLE DIAMETERS

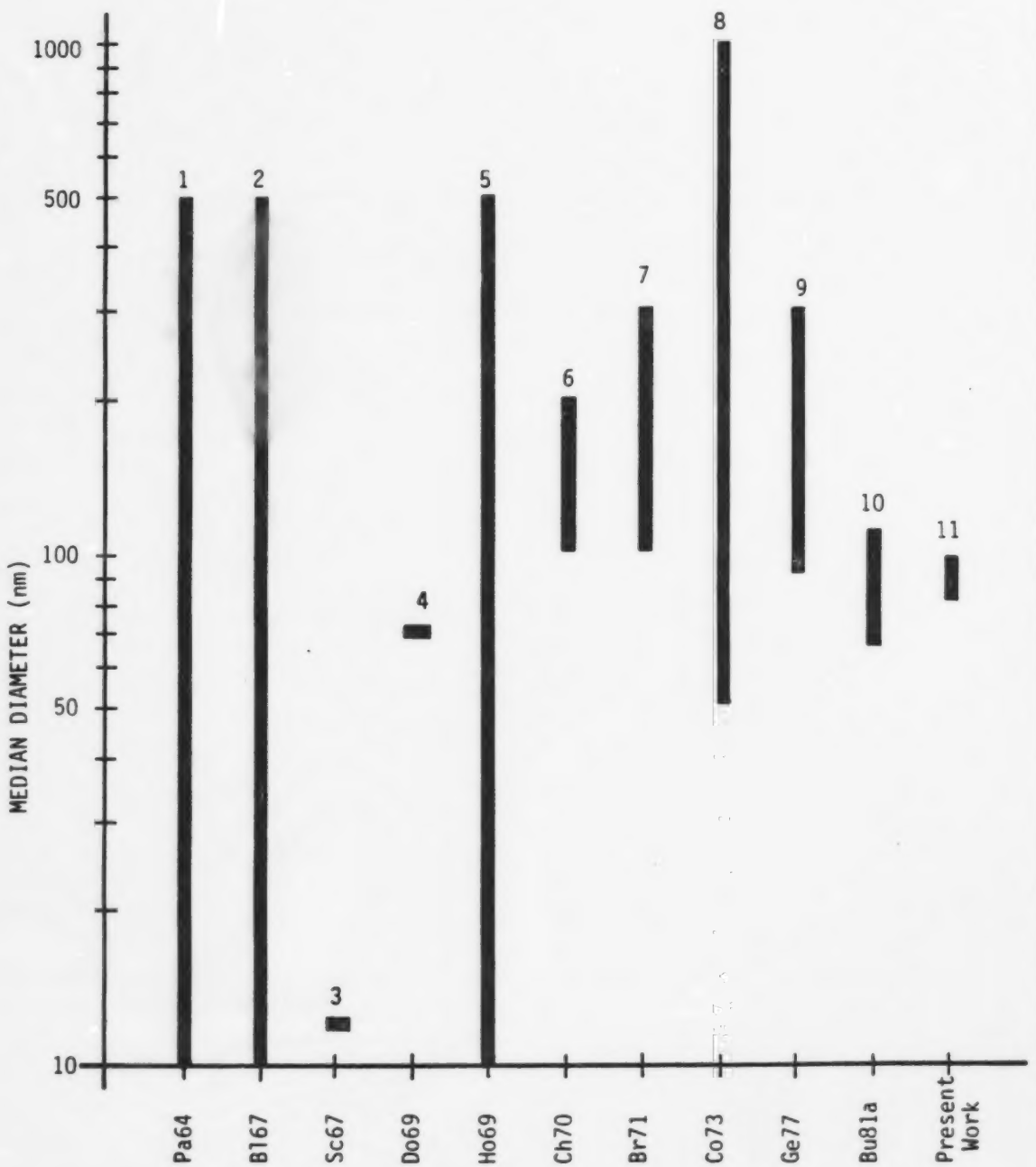


FIGURE 34

COMPARISON OF CARRIER AEROSOL DIAMETER MEASUREMENTS

NOTES ON FIGURE 34

1. A casella cascade impactor was used for measurements. The size range was <0.5 with no specified minimum.

2. The size range shown is not exact. Using diffusion batteries, the size was indicated to be less than 0.5 μm.

3. Diffusion tubes were used.

4. Sizes obtained by diffusion batteries.

5. Cascade impactor was used.

6. Results were obtained by using a Zeleny tube ion collector and diffusion batteries. Similar results (using the same method) were obtained by other workers (Bi71; Pr70).

7. Diffusion batteries were used.

8. Impactors were used.

9. A round jet cascade impactor and four diffusion batteries were used.

10. Diffusion batteries employed were identical to those used in the present work.

11. The specified range is for RnWL measured in the trackless mine.

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APPENDIX A

Schedule for Measurements

(a) Jan 29 - Feb 6

(b) Feb 7 - Feb 8

(a) Jan 29 - Feb 6

Schedule Revised on January 25, 1985.

Sampling Time = 10 mins for all measurements.

Diffusion Batteries: DBs counting: 2-4, 9-12, 85-95,240-250 (min)

Extra count for reference filters: 650-750 (min)

Sample #1. Ufs counting: 2-5, 9-25, 40-70, 360-460 (min)

Ref., D.B.#3 Sampling: 8.00-8.10
D.B. #4 & 5 Counting: 8.12-8.14, 8.19-8.22, 9.35-9.45, 12.10-12.20

Extra count for reference filter: 6.50-8.30

Sample #2 Sampling: 8.13-8.23
Ref., D.B. #3 Counting: 8.25-8.27, 8.32-8.35, 10.00-10.10, 12.23-12.33

Extra count for reference filter: 7.03-8.43

Unattached Fractions:

Sample #1 Sampling: 10.01-10.11
Counting: 10.13-10.16, 10.20-10.36, 10.51-11.21, 4.11-5.5

Sample #2 Sampling: 10.35-10.45
Counting: 10.47-10.50, 10.54-11.10, 11.25-11.55, 4.45-6.

Sample #3 Counting intervals: 2-5, 9-25, 30-60, 360-460

Sampling: 12.22-12.32
Counting: 12.34-12.37, 12.41-12.57, 1.02-1.32, 6.32-8.12

Spare samples for Rn + Tn determination:

Counting intervals: 2-7, 340-350 min after 10 min samplin

Sample #1 & #2: Sampling: 10.22-10.3
Counting: 10.34-10.39, 4.12-4.22

Sample #3 & #4: Sampling: 12.38-12.48
Counting: 12.50-12.55, 6.28-6.38

Dated _____ Sheet AA Diffusion batteries #3 and #4
Unattached fraction wire screen

Trimet #3 Eff____ Pump #3 flowrate _____ Combined flowrate = _____

Trimet #4 Eff____ Pump #4 flowrate _____

Actual Time	Stopwatch time hr	min	Action to be taken
			Prepare for sampling through diffusion batteries. Load filter #3 in D.B. #3, filter #4 in D.B. #4. Pump #3 with D.B. #3, Pump #4 with D.B. #4.
_____		00	Start sampling through D.B. #3 and D.B. #4.
_____		10	Stop sampling through D.B. #3 and D.B. #4. Load filter #3 from D.B. #3 into
----------		--	Trimet #3 and filter #4 in Trimet #4.
_____		12	Start counting in Trimet #3 and Trimet #4.
----------		--	Prepare for sampling (sample #2) through both D.B.s (filter #5 in D.B. #3 and filter #6 in D.B. #4).
_____		13	Start sampling through both D.B.s.
----------		--	
_____		14	Stop counting in Trimet #3 and Trimet #4.
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
_____		19	Start counting in Trimet #3 and Trimet #4.
----------		--	
_____		22	Stop counting in Trimet #3 and Trimet #4
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
			Remove (and save) both filters from Trimet #3 and #4.
_____		23	Stop sampling in D.B. #3 and D.B. #4. Load filter #5 in Trimet #3 and filter
----------		--	#6 in Trimet #4.
_____		25	Start counting in Trimet #3 and Trimet #4.
----------		--	
_____		27	Stop counting in Trimet #3 and Trimet #4.
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____

Dated _____ Sheet AA D.B. #3 and 4 Wire screen

Actual Time	Stopwatch time hr	min	Action to be taken
_____		32	Start counting in Trimet #3 and Trimet #4
----------		--	
_____		35	Stop counting in Trimet #3 and Trimet #4
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
			Remove (and save) both filters from Trimets #3 and #4.
			Load filter #3 in Trimet #3 and filter #4 in Trimet #4.
_____	1	35	Start counting in Trimet #3 and Trimet #4
----------		--	
_____	1	45	Stop counting in Trimet #3 and Trimet #4
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
			Remove (and save) both filters from Trimets.
			Load filter #5 in Trimet #3 and filter #6 in Trimet #4.
			Prepare for sampling through the wire screen.
			Load filter #7 in the wire screen filter holder.
			Join pump #3 and pump #4 together to sample through the wire screen.
_____	2	00	Start counting in Trimet #3 and Trimet #4.
----------		--	
_____	2	01	Start sampling through the wire screen
----------		--	
_____	2	10	Stop counting in Trimet #3 and Trimet #4.
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
			Remove (and save) filter #5 and filter #6 from the Trimets
_____	2	11	Stop sampling through the wire screen
----------		--	Load filter #7 from the wire screen into Trimet #3

Dated _____ Sheet AA D.B. #3 and #4
Wire screen

Actual Time	Stopwatch time hr	Stopwatch time min	Action to be taken
_____	2	13	Start counting in Trimet #3.
----------		---	
_____	2	16	Stop counting in Trimet #3.
----------		---	Record counts _____
_____	2	20	Start counting in Trimet #3. Prepare for sample #2 of wire screen.
----------		--	Load filter #8 in wire screen filter holder. Use pump #3 and pump #4 joined together.
			See sheet AA-a or continue
_____	2	35	Start sampling through wire screen.
----------		--	
_____	2	36	Stop counting in Trimet #3
----------		--	Record counts _____
_____	2	45	Stop sampling through wire screen. Load filter #8 from the wire screen
----------		--	into Trimet #4
_____	2	47	Start counting in Trimet #4.
----------		--	
_____	2	50	Stop counting in Trimet #4
----------			Record counts _____
_____	2	51	Start counting in Trimet #3
----------		--	
_____	2	54	Start counting in Trimet #4
----------		--	
_____	3	10	Stop counting in Trimet #4
----------			Record counts _____
_____	3	21	Stop counting in Trimet #3
----------		--	Record counts _____
			Remove (and save) filter #7 from Trimet #3 for above ground counting.
_____	3	25	Start counting in Trimet #4
----------		--	
_____			LUNCH BREAK _____

AA-4

Dated _____ Sheet AA D.B. #3 and #4
Wire screen

Actual Time	Stopwatch time hr	min	Action to be taken
_____	3	55	Stop counting in Trimet #4
----------			Record counts _____
			Remove (and save) filter #8 from Trimet #4 for above ground counting
_____	4	10	Load filter #3 in Trimet #3 and filter #4 in Trimet #4.
----------		--	Start counting in Trimet #3 & Trimet #4. Prepare for sampling (sample #3) through the wire screen. Load filter #9 in the wire screen filter holder. (Pump #3 and pump #4 joined together)
_____	4	20	Stop counting in Trimet #3 and Trimet #4.
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
			Remove (and discard) filters from Trimet #3 and Trimet #4. Load filter #5 in Trimet #3 and filter #6 in Trimet #4.
_____	4	22	Start sampling through the wire sreen
----------		--	
_____	4	23	Start counting in Trimet #3 and Trimet #4
----------		--	
_____	4	32	Stop sampling through the wire screen
----------		--	
_____	4	33	Stop counting in Trimet #3 and Trimet #4.
----------		--	
			Trimet #3 - Record counts _____
			Trimet #4 - Record counts _____
			Remove (and discard) both filters from Trimet #3 and Trimet #4
			Quickly load filter #9 from wire screen filter holder into Trimet #3
_____	4	34	Start counting in Trimet #3
----------		--	
_____	4	37	Stop counting in Trimet #3
----------			Record counts _____

See sheet AA-b or continue

_____	4	41	Start counting in Trimet #3
----------		--	

AA-a

Actual Time	Stopwatch time hr	min	Action to be taken
			Load filter #W1 in open face filter holder.
_____	2	22	Sample through filter #W1.
----------		--	
_____	2	32	Stop sampling. Load filter #W1 in Trimet #4.
----------		--	
_____	2	34	Start counting in Trimet #4.
----------		--	
_____	2	35	Start sampling through wire screen.
----------		--	
_____	2	36	Stop counting in Trimet #3.
----------			Record counts _____
_____	2	39	Stop counting in Trimet #4.
----------		--	Record counts _____
			See the schedule (Sheet AA-3)
_____	8	00	Load filter #7 in Trimet #3. Load filter #W1 in Trimet #4
----------		--	
_____	8	11	See schedule.
_____	8	12	Start counting in Trimet #4.
----------		--	
_____	8	22	Stop counting in Trimet #4
----------		--	Record counts _____
			Remove (and discard) filter #W1 from Trimet #4.
			See the schedule (Sheet AA-5)

Dated _____ Sheet AA D.B. #3 and #4
Wire screen

Actual Time	Stopwatch time hr	Stopwatch time min	Action to be taken
_____	4	57	Stop counting in Trimet #3
----------			Record counts _____
_____	5	02	Start counting in Trimet #3
----------		--	
			START PACKING UP TO LEAVE
_____	5	32	Stop counting in Trimet #3
			Record counts _____
			Remove (and save) filter #9 from Trimet #3 for above ground counting.
			END OF UNDERGROUND WORK
			See sheet AA-a or continue
_____	8	00	Start preparing for counting. Load filter #7 in Trimet #3.
----------		--	
_____	8	11	Start counting in Trimet #3
----------		--	
			Load filter #8 in Trimet #4
_____	8	45	Start counting in Trimet #4
----------		--	
_____	9	51	Stop counting in Trimet #3
----------		--	Record counts _____
			Remove (and discard) filter #7
_____	10	25	Stop counting in Trimet #4
----------		--	Record counts _____
			Load filter #9 in Trimet #3
_____	10	32	Start counting in Trimet #3

			See sheet AA-b or continue
REMINDER:			Check pump flow rates and plug in chargers
_____	12	12	Stop counting in Trimet #3
----------			Record counts _____
			Remove (and discard) filter #9
			END OF THE DAY

AA-b

Actual Time	Stopwatch time hr	min	Action to be taken
_____	4	35	Load filter #W3 in an open face filter holder.
----------		--	
_____	4	37	Stop counting in Trimet #3.
----------		--	Record counts _____
_____	4	38	Start sampling through #W3.
----------		--	
_____	4	41	Start counting in Trimet #3.
----------		--	
_____	4	48	Start sampling through filter #W3. Load filter #W3 in Trimet #4.
----------		--	
_____	4	50	Start counting in Trimet #4.
----------		--	
_____	4	55	Stop counting in Trimet #4.
----------		--	Record counts _____
	See the schedule (Sheet AA-4)		
_____	10	26	Load filter #W3 in Trimet #4.
----------		--	
_____	10	28	Start counting in Trimet #4.
----------		--	
_____	10	38	Stop counting in Trimet #4.
----------		--	Record counts _____
	See the schedule (Sheet AA-5)		

BB-1

Dated _____ Sheet BB Diffusion batteries Ref. & #5
Unattached fraction wire screen Ref.

Trimet #1 Eff ____ Pump #1 flowrate _____ Combined flowrate = _____

Trimet #2 Eff ____ Pump #2 flowrate _____

Actual Time	Stopwatch time hr	min	Action to be taken
			Prepare for sampling through diffusion batteries. Load filter #A in the Ref. and filter #B in D.B. #5. Pump #1 with the Ref. Pump #2 with D.B. #5.
_____		00	Start sampling through the Ref and D.B. #5.
_____		10	Stop sampling through the Ref and D.B. #5. Load filter #A from the Ref into
----------		--	Trimet #1 and filter #B in Trimet #2.
_____		12	Start counting in Trimet #1 and Trimet #2.
----------		--	Prepare for sampling (sample #2) through both D.B.s (filter #C the Ref and filter #D in D.B. #5).
_____		13	Start sampling through both D.B.s.
----------		--	
_____		14	Stop counting in Trimet #1 and Trimet #2.
----------		--	
			Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
_____		19	Start counting in Trimet #1 and Trimet #2.
----------		--	
_____		22	Stop counting in Trimet #1 and Trimet #2
----------		--	
			Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
			Remove (and save) both filters from Trimet #1 and #2.
_____		23	Stop sampling in the Ref and D.B. #5. Load filter #C in Trimet #1 and filter
----------		--	#D in Trimet #2.
_____		25	Start counting in Trimet #1 and Trimet #2.
----------		--	
_____		27	Stop counting in Trimet #1 and Trimet #2.
----------		--	
			Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____

Dated _____ Sheet BB the Ref and D.B.#5 Wire screen Ref.

Actual Time	Stopwatch time hr	min	Action to be taken
		32	Start counting in Trimet #1 and Trimet #2
----------		--	
		35	Stop counting in Trimet #1 and Trimet #2
----------		--	
			Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
			Remove (and save) both filters from Trimets #1 and #2.
			Load filter #A in Trimet #1 and filter #B in Trimet #2.
_____	1	35	Start counting in Trimet #1 and Trimet #2
----------		--	
_____	1	45	Stop counting in Trimet #1 and Trimet #2
----------		--	
			Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
			Remove (and save) both filters from Trimets.
			Load filter #C in Trimet #1 and filter #D in Trimet #2.
			Prepare for sampling through the wire screen.
			Load filter #E in the wire screen reference filter holder.
			Join pump #1 and pump #2 together to sample through the wire screen reference.
_____	2	00	Start counting in Trimet #1 and Trimet #2.
----------		--	
_____	2	01	Start sampling through the wire screen reference.
----------		--	
_____	2	10	Stop counting in Trimet #1 and Trimet #2.
----------		--	
			Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
			Remove (and save) filter #C and filter #D from the Trimets
_____	2	11	Stop sampling through the wire screen reference.
----------		--	
			Load filter #E from the wire screen reference into Trimet #1

Dated _____ Sheet BB the Ref & D.B.#5 Wire screen Ref.

Actual Time	Stopwatch time hr	min	Action to be taken
_____	2	13	Start counting in Trimet #1.
----------		---	
_____	2	16	Stop counting in Trimet #1.
----------		---	Record counts _____
_____	2	20	Start counting in Trimet #1. Prepare for sample #2 of wire screen
----------		--	reference. Load filter #G in wire screen reference filter holder. Use pump #1 and pump #2 joined together.
			See sheet AA-a or continue
_____	2	35	Start sampling through wire screen.
----------		--	
_____	2	36	Stop counting in Trimet #1
----------		--	Record counts _____
_____	2	45	Stop sampling through wire screen reference. Load filter #8 from the wire
----------		--	screen reference into Trimet #2 .
_____	2	47	Start counting in Trimet #2.
----------		--	
_____	2	50	Stop counting in Trimet #2
----------			Record counts _____
_____	2	51	Start counting in Trimet #1
----------		--	
_____	2	54	Start counting in Trimet #2
----------		--	
_____	3	10	Stop counting in Trimet #2
----------			Record counts _____
_____	3	21	Stop counting in Trimet #1
----------		--	Record counts _____
			Remove (and save) filter #E from Trimet #1 for above ground counting.
_____	3	25	Start counting in Trimet #2
----------		--	
_____			LUNCH BREAK _____

Dated _____ Sheet BB the Ref & D.B.#5 Wire screen Ref.

Actual Time	Stopwatch time hr	min	Action to be taken
_____	3	55	Stop counting in Trimet #2
----------			Record counts _____
			Remove (and save) filter #G from Trimet #2 for above ground counting
_____	4	10	Load filter #A in Trimet #1 and filter #B in Trimet #2.
----------		--	Start counting in Trimet #1 and Trimet #2. Prepare for sampling (sample #3) through the wire screen. Load filter #H in the wire screen filter holder. (Pump #1 and pump #2 joined together)
_____	4	20	Stop counting in Trimet #1 and Trimet #2.
----------		--	Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
			Remove filters from Trimet #1 and Trimet #2. Save filter #A for above ground counting. Load filter #C in Trimet #1 and filter #D in Trimet #2.
_____	4	22	Start sampling through the wire sreen
----------		--	
_____	4	23	Start counting in Trimet #1 and Trimet #2
----------		--	
_____	4	32	Stop sampling through the wire screen
----------		--	
_____	4	33	Stop counting in Trimet #1 and Trimet #2.
----------		--	Trimet #1 - Record counts _____
			Trimet #2 - Record counts _____
			Remove both filters from Trimet #1 and Trimet #2. Save filter #C for above ground counting.
			Quickly load filter #H from wire screen filter holder into Trimet #1
_____	4	34	Start counting in Trimet #1
----------		--	
			See sheet BB-b or continue
_____	4	37	Stop counting in Trimet #1
----------			Record counts _____

Dated _____ Sheet BB the Ref & D.B.#5 Wire screen

Actual Time	Stopwatch time hr	min	Action to be taken
_____	4	41	Start counting in Trimet #1
----------		--	
_____	4	57	Stop counting in Trimet #1
----------			Record counts _____
_____	5	02	Start counting in Trimet #1
----------		--	
_____			START PACKING UP TO LEAVE _____
_____	5	32	Stop counting in Trimet #1
			Record counts _____
			Remove (and save) filter #H from Trimet #1 for above ground counting.
_____			END OF UNDERGROUND WORK _____
			See sheet AA-a or continue
_____	8	00	Start preparing for counting. Load filter #E in Trimet #1.
----------		--	
_____	8	11	Start counting in Trimet #1
----------		--	
			Load filter #G in Trimet #2
_____	8	45	Start counting in Trimet #2
----------		--	
_____	9	51	Stop counting in Trimet #1
----------		--	Record counts _____
			Remove (and discard) filter #E
_____	10	25	Stop counting in Trimet #2
----------		--	Record counts _____
			Load filter #H in Trimet #1
_____	10	32	Start counting in Trimet #1

			See sheet AA-b or continue
REMINDER:			Check pump flow rates and plug in chargers
_____	12	12	Stop counting in Trimet #1
----------			Record counts _____
			Remove (and discard) filter #H
_____			END OF THE DAY _____

BB-a

Actual Time	Stopwatch time hr	min	Action to be taken
			Load filter #W2 in open face filter holder
_____	2	22	Start sampling through filter #W2
----------		--	
_____	2	32	Stop sampling. Load filter #W2 in Trimet #2.
----------		--	
_____	2	34	Start counting in Trimet #2.
----------		--	
_____	2	35	Start sampling through the wire screen references.
----------		--	
_____	2	36	Stop counting in Trimet #1.
----------		--	Record counts _____
_____	2	39	Stop counting in Trimet #2.
----------		--	Record counts _____
	See the schedule (Sheet BB-3)		
_____	8	00	Load filter #E in Trimet #1. Load filter #W2 in Trimet #2.
----------		--	
_____	8	11	See schedule.
_____	8	12	Start counting in Trimet #2.
----------		--	
_____	8	22	Stop counting in Trimet #2.
----------		--	Record counts _____
			Remove (and discard) filter #W2 from Trimet #2.
	See the schedule (Sheet BB-5)		

Actual Time	Stopwatch time hr	min	Action to be taken
_____	4	35	Load filter #W4 in an open face filter holder.
----------		--	
_____	4	37	Stop counting in Trimet #.
----------		--	Record counts _____
_____	4	38	Start sampling through filter #W4.
----------		--	
_____	4	41	Start counting in Trimet #1.
----------		--	
_____	4	48	Stop sampling through filter #W4. Load filter #W4 in Trimet #2.
----------		--	
_____	4	50	Start counting in Trimet #2.
----------		--	
_____	4	55	Stop counting in Trimet #2.
----------			Record counts _____
	See the schedule (Sheet BB-4)		
_____	10	26	Load filter #W4 in Trimet #2.
----------		--	
_____	10	28	Start counting in Trimet #2.
----------		--	
_____	10	38	Stop counting in Trimet #2.
----------		--	Record counts _____
			Load filter #A in Trimet #2.
_____	10	50	Start counting in Trimet #2. Load filter #C in Trimet #4.
----------		--	
_____	11	03	Start counting in Trimet #4.
----------		--	
_____	12	12	Stop counting in Trimet #1.
----------		--	Record counts _____
_____	12	30	Stop counting in Trimet #2
----------			Record counts _____
_____	12	43	Stop counting in Trimet #4
----------			Record counts _____
			END OF DAY

(b) Feb 7 - Feb 8

Sampling and Counting Schedule:

	Species & Sample No.	Sampling Time	Counting Time	Counting Interval
Diffusion Batts.	ThB #1	8.00-8.15	12.45-1.00	270-285
Unattached Fr.	ThB #1	8.17-8.32	1.02-1.32	270-300
Diffusion Batts.	Rn ds #1	8.35-8.40	8.42-8.47	2-7
Unattached Fr.	Rn ds #1	8.45-8.50	8.52-8.57	2-7
Diffusion Batts.	Rn ds #2	9.05-9.10	9.12-9.17	2-7
Unattached Fr.	Rn ds #2	9.15-9.20	9.22-9.27	"
Diffusion Batts.	Rn ds #3	9.35-9.40	9.42-9.47	"
Unattached Fr.	Rn ds #3	9.45-9.50	9.52-9.57	"
Diffusion Batts.	Rn ds #4	10.05-10.10	10.12-10.17	"
Unattached Fr.	Rn ds #4	10.15-10.20	10.22-10.27	"
Diffusion Batts.	ThB #2	11.25-11.40	5.10-5.25	330-345
Unattached Fr.	ThB #2	11.42-11.57	5.27-5.57	330-360
Unattached Fr.	ThB #3	12.03-12.18	5.48-6.18	"
Diffusion Batts.	ThB #3	12.35-12.50	6.20-6.35	330-345
Diffusion Batts.	ThB #4	12.57-1.12	6.42-6.57	"
Unattached Fr.	ThB #4	1.15-1.30	7.00-7.30	330-360

Dated: _____

AA		BB	
Trimet #3 - Eff Trimet #4 - Eff	Pumps #3 & #4 D.B.3, D.B.4 and WS	Trimet #1 - Eff Trimet #2 - Eff Trimet #5 - Eff	Pumps #1 & #2 D.B.5, Ref. and WS Ref.

Actual Time	Stopwatch time hr	Stopwatch time min	Action to be taken
			Prepare for sampling for ThB through diffusion batteries and reference. Filter #A (ref.) - #1 (D.B.3) #B (D.B.5) - #2 (D.B.4) Pump #3 - D.B. #3, #1 ref. #4 - D.B. #4, #2 D.B.5
_____		00	Start sampling through D.B.s. Load filters in wire screen and reference for sampling unattached ThB. Filter #C (ref) #3 (WS)
_____		15	Stop sampling through diffusion batteries.
----------		--	Remove pumps and join pump #1 and 2 to WS ref., pump #3 and 4 to WS
_____		17	Start sampling through WS and WS ref.
----------		--	Remove filters from D.B.s and their reference and save them for later counting (underground). Load fresh filters in D.B.s for sampling Rn daughters. Filter #D - Ref. - #4 (D.B.3) #E - (D.B.5) - #5 (D.B.4)
_____		32	Stop sampling through wire screen and reference. Save filters for later
----------		--	counting (underground). Quickly join pump #1 to D.B. ref., #2 to D.B.5, #3 to D.B.3 and #4 to D.B.4.
_____		35	Start sampling through D.B.s for radon daughters. Load fresh filters for wire
----------		--	screen sampling. Filter #G (ref.), filter #6 (WS).
_____		40	Stop sampling through D.B.s. Quickly load filters in Trimets.
----------		--	Ref. - T#1 D.B.3 - T#3 D.B.5 - T#2 D.B.4 - T#4
_____		42	Start counting in all Trimets. Join pump #1 and 2 to WS ref.
----------		--	pump #3 and 4 to WS
_____		45	Start sampling through WS and its ref.
----------		--	
_____		47	Stop counting in all Trimets.
----------		--	Record counts _____ (Trimet #1 or 3) _____ (Trimet #2 or 4) (Discard all filters)

Actual Time	Stopwatch time		Action to be taken
	hr	min	
_____		50	Stop sampling through WS and WS ref. Quickly load filters into Trimets.
----------		--	From ref to Trimet #1 From WS to Trimet #3
_____		52	Start counting in Trimets (5 min count) Load fresh filters for D.B. sampling
----------		--	for Rn ds. Filter #H - ref #7 - D.B.3 #J - D.B.5 #8 - D.B.4
_____		57	Stop counting in Trimets.
----------		--	
			Record counts _____ (Trimet #1 or 3)
			(Discard filters) Join pumps in the usual manner for D.B. sampling. Pump #1 - ref #3 D.B.3 #2 - D.B.5 #4 D.B.4
_____	1	05	Start sampling in diffusion batteries. Load fresh filters for WS sampling.
----------		--	filter #K (WS ref) #9 (WS)
_____	1	10	Stop sampling in D.B.5. Load filters in Trimets in the usual
----------		--	way. Ref - T#1 D.B.3 - T#3 D.B.5 - T#2 D.B.4 - T#4
_____	1	12	Start counting in Trimets. Join pumps for WS sampling in the usual
----------		--	way.
_____	1	15	Start sampling for WS.
----------		--	
_____	1	17	Stop counting in Trimets.
----------		--	
			Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			(Discard all filters)
_____	1	20	Stop sampling through WSs. Load filters in usual Trimets.
----------		--	Ref - T#1 WS - T#3
_____	1	22	Start counting in Trimets.
----------		--	
_____	1	27	Stop counting in Trimets.
----------		--	Record counts _____ (Trimet #1 or 3)
			(Discard filters) Prepare for sample #3 for Rn ds through D.B.s Filter #L (ref) filter #10 (D.B.3) #M (D.B.5) #11 (D.B.4) Join pumps in usual way.

Actual Time	Stopwatch time		Action to be taken
	hr	min	
_____	1	35	Start sampling through D.B.s.
			Load fresh filters for WS sampling
----------		--	filter #N (ref.) filter #12 (WS)
_____	1	40	Stop sampling through D.B.s.
			Load filters in Trimets in usual way.
----------		--	
_____	1	45	Start sampling through WS.
----------		--	
_____	1	47	Stop counting in Trimets.
----------		--	Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			(Discard all filters)
_____	1	50	Stop sampling through WS.
			Load filters into usual Trimets.
----------		--	
_____	1	52	Start counting in Trimets.
----------		--	
_____	1	57	Stop counting.
----------			Record counts _____ (Trimet #1 or 3)
			(Discard filters)
			Load fresh filters for D.B. sample #4 for Rn ds.
			Filter #O (ref) filter #13 (D.B.3)
			#P (D.B.5) #14 (D.B.4)
			Join pumps in usual manner.
_____	2	05	Start smpling through D.B.s. Prepare for WS sampling.
----------		--	Filter #Q (ref) filter #15 (WS)
_____	2	10	Stop sampling through D.B.s.
			Load filters in usual Trimets.

_____	2	12	Start counting.
			Join pumps for WS sampling.
----------		--	
_____	2	15	Start WS sampling.
----------		--	
_____	2	17	Stop counting.
----------		--	Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			(Discard all filters)
_____	2	20	Stop WS sampling.
			Load filters in usual manner.

Actual Time	Stopwatch time hr	min	Action to be taken
_____	2	22	Start counting.
----------		--	
_____	2	27	Stop counting.
----------			Record counts_____ (Trimet #1 or 3)
			(Discard filters)
			LUNCH BREAK
_____	3	20	Prepare for D.B. sample #2 for ThB. #R (ref) #16 (D.B.3) #S (D.B.5) #17 (D.B.4) Join pumps in usual way.
_____	3	25	Start sampling. Prepare for WS Sample #7 for ThB. filter #T (ref) #18 (WS)
_____	3	40	Stop sampling. Quickly join pumps to WS ref.

_____	3	42	Start sampling through WS and ref. Save filters from D.B.s for above
----------			ground counting.
_____	3	57	Stop sampling through WS and ref. Do not remove pumps.
----------			Change fresh filters in WS and ref. filter #U (ref) #19 (WS) Save previous filters for above ground counting.
_____	4	03	Start sampling through WS and ref.

_____	4	18	Stop sampling through WS and ref. Remove and save filters for above
----------			ground counting. Load fresh filters for D.B. sample #3 #V (ref) #20 (D.B.3) #W (D.B.5) #21 (D.B.4) Join pumps in usual way.
_____	4	35	Start sampling through D.B.s. Load filter #A, B in Trimets #1, 2,
----------			filter #1, 2 in Trimets #3, 4
_____	4	45	Start counting in all Trimets.

_____	4	50	Stop sampling through D.B.s. Do not remove pumps.
----------			Save filters for above ground counting. Load fresh filters for sample #4 with D.B.s #X (ref) #22 (D.B.3) #Y (D.B.5) #23 (D.B.4)

Actual Time	Stopwatch time hr	min	Action to be taken
_____	4	57	Start sampling through D.B.s.
----------		--	
_____	5	00	Stop counting in all Trimeta.
----------		--	Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			Discard all filters and quickly load filter #C in Trimet #1 filter #3 in Trimet #3
_____	5	02	Start counting in Trimet #1 and 3. Prepare for WS sample #4, filter #2
----------		--	(ref.)
_____	5	12	Stop sampling through D.B.s #24 (WS). Join pumps to WS and ref.

_____	5	15	Start sampling through WS and ref. Save filters from D.B.s for above
----------			ground counting.
_____	5	30	Stop sampling through WS and ref. Save filters for above ground counting.

_____	5	32	Stop counting in Trimet #1 and 3.
----------		--	Record counts _____ (Trimet #1 or 3)
			(Discard filters)
_____			END OF UNDERGROUND WORK _____
_____	9	00	Load filters #R and S in Trimets #1 and 2, #16 and 17 in Trimets #3 and 4
----------		--	
_____	9	10	Start counting in all Trimets.
----------		--	
_____	9	25	Stop counting in all Trimets.
----------		--	Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			Quickly discard these filters and load filter #T Trimet #1 filter #18 Trimet #3
_____	9	27	Start counting. Load filter #U Trimet #2
----------		--	#19 Trimet #4
_____	9	48	Start counting in Trimet #2 and 4.
----------		--	

Actual Time	Stopwatch time		Action to be taken
	hr	min	
_____	10	18	Stop counting in Trimet #2 and 4
----------		--	Record counts _____ (Trimet #2 or 4)
			Quickly discard these filters and load filter #V & W in Trimet #1 and 2 filter #20 & 21 in Trimet #3 and 4
_____	10	20	Start counting in all Trimets.
----------		--	
_____	10	35	Stop counting in all Trimets.
----------		--	Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			(Discard all filters)
			Load filters #X & Y in Trimet #1 & 2 filter #22 & 23 in Trimet #3 & 4
_____	10	42	Start counting in all Trimets.
----------		--	
_____	10	57	Stop counting in all Trimets.
----------		--	Record counts _____ (Trimet #1 or 3)
			_____ (Trimet #2 or 4)
			Discard all filters and quickly load filters #2 - Trimet #1 #24 - Trimet #3
_____	11	00	Start counting.
----------		--	
_____	11	30	Stop counting.
----------		--	Record counts _____ (Trimet #1 or 3)
			(Discard all filters)

END OF DAY

APPENDIX B

Raw Data from the Mine Measurements for Unattached Fractions, Activity Size Distributions, Aerosol Size Distributions (Diffusion Battery Data), and Working Levels of Radon and Thoron Progeny

(a) Track mine: Jan 29 - Feb 1

(b) Trackless mine: Feb 4 - Feb 8

MINE DATA

Dated Jan 29 (Track)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(5)
9:00	3.5	0.444	Ref.	868	954	1307	361	1972
	3.9	0.451	D.B.3	670	770	1013	339†	
	4	0.453	D.B.4	435	643	630	212	
	3.1	0.458	D.B.5	189	231	331	115	
9:15	3.5	0.444	Ref.	899	967	1137	402	2005
	3.9	0.451	D.B.3	713	858	904	344†	
	4	0.453	D.B.4	512	532	677	241	
	3.1	0.458	D.B.5	186	210	236	130	

† Trimet Eff. = 0.468.

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
11:05	5.6	0.458	Ref				
	6.55	0.453	Back-up	Error in filter loading			
11:40	5.6	0.458	Ref	1830	7027	9634	4047
	6.55	0.453	Backup	2235	8440	11980	4913
13:15	5.6	0.444	Ref	1467	5927	8273	3376
	6.55	0.468	Back-up	2404	8472	919*	4239**

* Counts taken during transit. Unacceptably low counts

** Trimet Eff. = 0.451

PROCESSED MINE DATA Dated Jan 29 (Track)

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
11:05	Ref Back-up	----			
11:40	Ref. Back-up	24.4 28.7	10.5 11.4	4.7 4.1	1.02 1.07
13:15	Ref. Back-up	----			

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:22	5.6	0.458	3123	463
11:22	6.55	0.453	3276	500
13:38	5.6	0.458	2474	363
13:38	6.55	0.453	3348	557

MINE DATA

Dated Jan 30 (Track)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(50
8:45	3.6	0.43	Ref.	679	728	1014	312	1875
	3.9	0.435	D.B.3	582	629	904	279	
	4	0.457	D.B.4	402	424	617	196	
	3.75	0.448	D.B.5	146	138	195	93	
9:00	3.6	0.43	Ref.	730	861	970	319	1942
	3.9	0.435	D.B.3	662	802	881	288	
	4	0.457	D.B.4	517	625	710	239	
	3.75	0.448	D.B.5	189	186	230	110	

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
10:50	5.1	0.43	Ref	2148	8297	11024	4559
	6.5	0.435	Back-up	2408	8957	11980	5091
11:25	5.1	0.448	Ref	2073	8374	10834	4465
	6.5	0.457	Backup	2169	8892	11521	4856
13:00	5.1	0.43	Ref	1693	6569	9767	3358
	6.5	0.435	Back-up	1787	7125	10695	4104

Total Aerosol Size Distribution Data Dated Jan 30 (Track)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
9.40	65K	47K	31K	13K	59K
11.40	62K	48K	36K	8K	62K
12.50	50K	32K	26K	15K	46K
13.50	41K	30K	22K	9K	42K

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
10:50	Ref	30.6	13.9	7.3	1.34
	Back-up	29	11.4	5.94	1.17
11:25	Ref.	24	13.4	7.8	1.29
	Back-up	18.6	11.05	6.4	1.06
13:00	Ref.	23.5	10.94	6	0.99
	Back-up	18.33	9.44	4.97	0.94

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:07	5.1	0.448	3216	498
11:07	6.5	0.457	3430	521
13:23	5.1	0.448	2579	389
13:23	6.5	0.457	2888	457

MINE DATA

Dated Jan 31 (Track)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(5)
8:55	3.3	0.436	Ref.	913*	1042*	1292	327	1962*
	3.8	0.453	D.B.3	735	890	1137	302	
	3.9	0.456	D.B.4	616	693	928	244	
	3.2	0.445	D.B.5	190†	221†	285	132	
9:10	3.3	0.436	Ref.	881	1050	1152	333	2079**
	3.85	0.453	D.B.3	859	1002	1078	370	
	3.75	0.456	D.B.4	661	709	812	287	
	3.2	0.445	D.B.5	226	231	260	132	

* Trimet Eff. = 0.445; † Trimet Eff. = 0.436
** Trimet Eff. = 0.446;

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
11:00	5.1	0.436	Ref	2249	8863	11059	4187
	6.1	0.453	Back-up	2563	10169	13521	5026
11:35	4.9	0.445	Ref	2580	10200	13436	5004
	6.15	0.456	Backup	2853	12348	15618	5924
13:20	4.75	0.436	Ref	3257	13156	19396	5691
	6.2	0.453	Back-up	3920	16029	23500	6683

Total Aerosol Size Distribution Data Dated Jan 31 (Track)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
9.35	51K	38K	26K	14K	44K
10.00	43K	33K	28K	8K	39K
11.50	49K	38K	31K	10K	54K
13.00	41K	33K	26K	7K	-
14.05	34K	26K	22K	12K	36K

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
11:00	Ref	29.2	14.6	8.2	1.2
	Back-up	28	14	7	1.18
11:35	Ref.	35.14	17.5	9.2	1.49
	Back-up	20.4	16.5	10.06	1.37
13:20	Ref.	42.9	23.9	13.06	1.78
	Back-up	36.2	21.5	12	1.54

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:17	4.9	0.445	3859	525
11:17	6.15	0.456	4147	596
13:33	4.75	0.445	5126	585
13:33	6.2	0.456	6228	698

MINE DATA

Dated Feb 1 (Track)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(5)
9:25	3.3	0.444	Ref.	3165	3856	4245	911	5202
	3.7	0.452	D.B.3	3231*	3930	2237†	899	
	3.5	0.454	D.B.4	2157*	2287	1437†	618	
	2.9	0.438	D.B.5	851	1034	1091	360	
9:40	3.3	0.444	Ref.	3375	4105	3688	966	5108
	3.7	0.452	D.B.3	3377	4182	3770	1026	
	3.6	0.454	D.B.4	1699	2068	1733	493	
	2.9	0.438	D.B.5	424	455	461	210	

* Counted for 1.5 min extra. † Counter stopped after 5 min due to pre-set time of 5 min, set by mistake.

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
11:30	5	0.444	Ref	8267	34108	39727	11108
	6.1	0.452	Back-up	9422	38081	44754	12310
12:05	5.1	0.438	Ref	8818	36507	42547	11596
	6.2	0.454	Backup	9100	40916	48203	13075
13:50	4.9	0.444	Ref	8110	33132	45312	9764
	6.1	0.452	Back-up	8978	36988	49497	10630

Total Aerosol Size Distribution Data Dated Feb 1 (Track)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
10.25	62K	53K	31K	7K	70K
12.20	74K	64K	34K	9.4K	74K
13.25	74K	62K	40K	8K	82K

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
11:30	Ref	67.7	50.8	41.6	3.24
	Back-up	69.8	45.6	36.4	2.89
12:05	Ref.	71.1	54.3	44.1	3.36
	Back-up	39.6	52.1	38.8	3.01
13:50	Ref.	75	51.5	39.6	2.91
	Back-up	57	43.8	37.1	2.50

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:47	5.1	0.438	14937	1292
11:47	6.2	0.454	17641	1351 *
14:03	4.8	0.438	12176	1026
14:03	6	0.454	15070	1188

* 11 minute counts

MINE DATA Dated Feb 4 (Trackless)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(5)
8:40	3.3	0.447	Ref.	2749	3100	3585	692	3685
	3.7	0.447	D.B.3	2751	3139	3835	854	--
	3.7	0.448	D.B.4	2200	2563	3003	587	--
	3.4	0.444	D.B.5	1073	1210	1451	382	--
8:55	3.3	0.447	Ref.	2525	2843	2762	570*	3607
	3.6	0.447	D.B.3	--	--	--	-	--
	3.7	0.448	D.B.4	2151	2716	2498	603	--
	3.3	0.444	D.B.5	1060	1217	1286	385*	

* 240-249 min count

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
10:45	5.3	0.447	Ref	6408	25674	31525	8009
	6	0.447	Back-up	6768	27434	33251	8690
11:20	5.2	0.444	Ref	6137	24926	30541	8432
	6	0.448	Backup	6576	26863	33236	9264
	6	0.419	WS	44	164	276	138
13:00	5.1	0.447	Ref†	6865	27225	38143	8519
	5.9	0.447	Back-up	6597	26508	37532	8299

† Sampling time = 11 min; counting intervals: 1-4,8-24,29-59,359-459

Total Aerosol Size Distribution Data Dated Feb 4 (Trackless)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
9.30	117K	104K	83K	44K	116K
11.30*	120K	120K	95K	59K	120K
12.40	116K	110K	90K	45K	245K
13.25*	135K	140K	100K	50K	130K

* D.B.3 data equal to or greater than the reference. Data ignored.

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
10:45	Ref	66.2	38.3	25.3	2.2
	Back-up	57.0	35.6	25	2.1
11:20	Ref.	61.5	38.1	25.6	2.4
	Back-up	57.3	35.9	23.2	2.2
	WS	0.92	0.32	0.1	0.04
13:00	Ref.	57.3	38.1	26.3	2.2
	Back-up	47.6	33.0	21.45	1.85

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:02	5.3	0.444	10015*	--
11:02	6		Filters blown away	
13:18	5.1		by wind	
13:18	5.9			

* Counting time = 2.367 - 7.367 min

MINE DATA

Dated Feb 5 (Trackless)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(5)
	3.25	0.434	Ref.	2635	3514	3398	529	3032*
8:40			D.B.3					
			D.B.4					
	3.75	0.458	D.B.5	1176	1653	1549	261	
			Ref.					
8:50	3.25	0.448	D.B.3	2563	2978	2712	508	
	3.75	0.449	D.B.4	1853	2272	2041	435	
			D.B.5					

* Trimet Eff. = 0.41

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
10:40	3.3	0.434	Ref	2880	11610	14187	3697
	3.7	0.448	Back-up	3039	12115	15168	3944
11:15	3.4	0.458	Ref	3073	12058	15204	3980
	3.7	0.449	Backup	3177	12377	15771	4303
	3.7	0.448	WS	11	58	73	60
13:05	3.1	0.434	Ref	2955	11492	16595	3557
	3.6	0.448	Back-up	3233	12885	18215	4030

Total Aerosol Size Distribution Data Dated Feb 5 (Trackless)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
9.20	130K	115K	110K	15K	130K
11.50	150K	120K	110K	32K	114K
12.50	185K	115K	65K	22K	>300K

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
10:40	Ref	47.5	28.5	19.27	1.67
	Back-up	48.1	26.4	16.16	1.54
11:15	Ref.	54.9	27.9	16.71	1.66
	Back-up	55.5	27.1	15.6	1.68
	WS	-0.01	0.14	0.11	0.025
13:05	Ref.	62.7	30.82	18.28	1.71
	Back-up	49.9	28.2	18.62	1.62

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:02	3.7	0.449	4951	474
11:02	3.5	0.458	4423	436
13:18	3.6	0.449	5450	475
13:18	3.3	0.458	5230	418

MINE DATA

Dated Feb 6 (Trackless)

Activity Size Distribution Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Interval Counts				
				I(1)	I(2)	I(3)	I(4)	I(5)
9:00	3.3	0.431	Ref.	2100	2430	2787	486	2500
	3.75	0.441	D.B.3	2073	2396	2754	488	
	3.75	0.441	D.B.4	1576	1888	2135	387	
	3.3	0.445	D.B.5	633	718	849	194	
9:15	3.3	0.431	Ref.	1908	2216	2039	540	2495
	3.75	0.441	D.B.3	2072	2440	2279	526	
	3.75	0.441	D.B.4	1650	2003	1923	472	
	3.3	0.445	D.B.5	642	781	752	262	

Unattached Fraction Data:

Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Interval Counts			
				I(1)	I(2)	I(3)	I(4)
11:05	5.1	0.431	Ref	5415	21429	26083	5633
	6.2	0.441	Back-up	5667	23365	28090	6078
11:40	5.3	0.445	Ref	5506	22287	26539	5547
	6	0.441	Backup	5813	23024	27675	6139
	6	0.415	WS	16	56	74	52
13:25	5	0.431	Ref	5181	20516	28532	6311*
	6	0.441	Back-up	5690	23805	33096	7192*

* Counted for extra 16 min.

Total Aerosol Size Distribution Data Dated Feb 6 (Trackless)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
9.45	150K	122K	90K	30K	142K
12.00	130K	110K	50K	30K	130K
13.05	128K	110K	100K	32K	135K

Unattached Fractions:

Sample Time	Filter mode	RaA pCi/L	RaB pCi/L	RaC pCi/L	ThB pCi/L
11:05	Ref	61.6	34	23	1.66
	Back-up	43.8	30	21	1.44
11:40	Ref.	51	32.6	23.6	1.52
	Back-up	52.7	29.8	21.2	1.5
	WS	0.22	0.07	0.05	0.01
13:25	Ref.	57.5	32.4	23.3	1.87
	Back-up	42.5	31.9	22.4	1.73

Working Level Data

Sample Time	Pump Flowrate (LPM)	Trimet Eff.	Interval Counts	
			I(1)	I(2)
11:22	5.3	0.445	9156	609
11:22	6	0.441	9427	682
13:38	5	0.445	8617	614*
13:38	5.7	0.441	8692	665*

* Counted extra 30 s.

DIFFUSION BATTERIES DATA — Feb 7 (Trackless)

Species	Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Counts
Rn ds	9:10	3.3	0.428	Ref	3101
		2.9	0.436	D.B.3	2465
		3.6	0.457	D.B.4	2592
		2.9	0.440	D.B.5	1063
Rn ds	9:40	3.1	0.428	Ref	2607
		2.9	0.436	D.B.3	2143
		3.6	0.457	D.B.4	2255
		3.2	0.440	D.B.5	940
Rn ds	10:10	3	0.428	Ref	2488
		2.9	0.436	D.B.3	1965
		3.6	0.457	D.B.4	2277
		2.9	0.440	D.B.5	872
Rn ds	10:40	3	0.428	Ref	2149
		2.8	0.436	D.B.3	1782
		3.5	0.457	D.B.4	1988
		3	0.440	D.B.5	823
^{212}Pb	8:40	3.25	0.428	Ref	904
		3.7	0.436	D.B.3	1014
		3.6	0.457	D.B.4	890
		3.25	0.440	D.B.5	455
^{212}Pb	12:05	2.8	0.428	Ref	645
		3.6	0.457	D.B.3	652
		3.5	0.436	D.B.4	795
		2.8	0.440	D.B.5	280
^{212}Pb	13:15	2.6	0.428	Ref	647
		3.5	0.436	D.B.3	828
		3.5	0.457	D.B.4	745
		2.6	0.440	D.B.5	234
^{212}Pb	13:40	2.5	0.428	Ref	590
		3.5	0.436	D.B.3	837
		3.4	0.440	D.B.4	687
		2.7	0.440	D.B.5	227

UNATTACHED FRACTION DATA — Feb 7 (Trackless)

Species	Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Counts
Rn ds	9:20	5.25	0.428	Ref	4719
		5.6	0.436	Backup	4931
Rn ds	9:50	5.1	0.428	Ref	3833
		5.5	0.436	Backup	3994
Rn ds	10:20	4.9	0.428	Ref	4008
		5.4	0.436	Backup	3816
Rn ds	10:55	4.8	0.428	Ref	4168
		5.6	0.436	Backup	4500
^{212}Pb	8:55	5.7	0.428	Ref	3194
		5.6	0.436	Backup	3083
^{212}Pb	12:25	4.4	0.428	Ref	2238
		5.7	0.436	Backup	2868
^{212}Pb	12:45*	4.1	0.44	Ref	2178
		6.0	0.457	Backup	2912
^{212}Pb	14:00	3.6	0.428	Ref	1794
		5.7	0.436	Backup	2811

* Sampling time = 15 min 11 sec

Total Aerosol Size Distribution Data Dated Feb 8 (Trackless)

Aerosol Concentration Data:

Time	Ref.	D.B.3	D.B.4	D.B.5	Ref.
10.05	101K	90K	80K	22K	120K
10.20	108K	103K	90K	22K	131K

DIFFUSION BATTERIES DATA — Feb 8 (Trackless)

Species	Sample Time	Pump Flowrate L/min	Trimet Eff.	Meas. Mode	Counts
Rn ds	8:45	3.1	0.438	Ref	2141
		3.5	0.448	D.B.3	2178
		3.7	0.451	D.B.4	1807
		3.5	0.44	D.B.5	789
Rn ds	9:15	3.3	0.438	Ref	2385
		3.7	0.448	D.B.3	2512
		3.9	0.451	D.B.4	2241
		3.5	0.44	D.B.5	896
Rn ds	*	3.6	0.438	Ref	1019
		3.8	0.448	D.B.3	2670
		4.0	0.451	D.B.4	2353
		3.4	0.44	D.B.5	915
^{212}Pb	*	3.2	0.438	Ref	794
		3.8	0.448	D.B.3	735
		3.5	0.451	D.B.4	682
		3.2	0.44	D.B.5	277
^{212}Pb	*	3.0	0.438	Ref	605
		3.8	0.448	D.B.3	762
		3.9	0.451	D.B.4	736
		3.4	0.44	D.B.5	298
^{212}Pb	*	3.5	0.438	Ref	859
		3.8	0.448	D.B.3	869
		-	0.451	D.B.4	-
		2.8	0.44	D.B.5	225
^{212}Pb	*	3.5	0.438	Ref	731
		3.8	0.448	D.B.3	742
		-	-	D.B.4	-
		2.8	0.44	D.B.5	52

*Suspected leak or pump #1 not working properly. Data ignored.

UNATTACHED FRACTION DATA — Feb 8 (Trackless)

Species	Sample Time	Pump Flowrate L/min	Trimet Eff.	Filter	Counts
Rn ds	8:55	5.6	0.438	Ref	4332
		6.2	0.448	Backup	4287
Rn ds	9:25	5.0	0.438	Ref	3563
		6.5	0.448	Backup	4480
Rn ds	9:55	5.1	0.438	Ref	4505
		6.8	0.448	Backup	5681
ThB	8:25	4:9	0.438	Ref	2571
		6.0	0.448	Backup	3019
ThB	12:00	2.75	0.438	Ref	1372
		6.5	0.448	Backup	2931
ThB	12:20	3.5	0.44	Ref	1723
		5.6	0.451	Backup	2501
ThB	13:35	3.5	0.438	Ref	1720
		4.7	0.448	Backup	2200

APPENDIX C

Processed Data for Aerosol and Activity Size Distributions and Unattached Fractions

(a) Track mine: Jan 29 - Feb 1

(b) Trackless Mine: Feb 4 - Feb 8

EXPLANATION OF SYMBOLS USED IN APPENDIX C

AMD	=	Activity Median Diameter
C_{ref}	=	Concentration of Radionuclide on Reference Filter
C_{WS}	=	Concentration of Radionuclide on Filter behind Wire Screen
$\bar{d}$	=	Count Median Diameter
D.B.	=	Diffusion Battery
E	=	Wire Screen Collection Efficiency
F_{exp}	=	Experimental Penetration Fraction (referred to as g_j in Text)
F_{theor}	=	Theoretical Penetration Fraction (referred to as $g_j^{(k)}$ in Text)
f_u	=	Unattached Fraction
GSD	=	Geometric Standard Deviation
P.I.	=	Performance Index
σ_g	=	Geometric Standard Deviation

TABLE 1. Activity Size Distribution Data (Track Mine) C-1

DATED	Time	Species	D.B. No.	Flowrate ml/s	F_{exp}	F_{theor}	AMD (μm)	GSD	P.I.
Jan. 29	9.00	Pb-212	3 4 5	65 66.6 51.7	.81 .51 .35	.82 .571 .287	0.0646	2.69	0.0700
	9.15	Pb-212	3 4 5	65 66.6 51.7	.73 .51 .37	.832 .575 .272	0.064	2.425	0.1200
Jan. 30	8.45	Po-218	3 4 5	65 66.6 62.5	.792 .533 .224	.807 .517 .237	0.0532	2.209	0.0197
	8.45	Pb-214	3 4 5	65 66.6 62.5	.82 .51 .117	.825 .486 .144	0.472	1.587	0.0300
	8.45	Bi-214	3 4 5	65 66.6 62.5	.74 .45 .20	.747 .444 .196	0.0435	2.427	0.0077
	8.45	Pb-212	3 4 5	65 66.6 62.5	.82 .53 .28	.82 .542 .266	0.057	2.296	0.0160
	9.00	Po-218	3 4 5	65 66.6 62.5	.71 .54 .40	.818 .564 .308	0.0628	2.619	0.1206
	9.00	Pb-214	3 4 5	65 66.6 62.5	.86 .625 .142	.862 .571 .198	0.0562	1.511	0.0656
	9.00	Bi-214	3 4 5	65 66.6 62.5	.884 .619 .192	.878 .608 .205	0.0594	1.344	0.0143
	9.00	Pb-212	3 4 5	65 66.6 62.5	.82 .69 .33	.851 .612 .345	0.072	2.474	0.0350
Jan. 31	8.55	Pb-214	3 4 5	63.3 65 53.3	.76 .574 .17	.812 .521 .213	0.0543	2.158	0.0657
	8.55	Bi-214	3 4 5	63.3 65 53.3	.756 .50 .295	.807 .532 .242	0.0569	2.403	0.0630
	8.55	Pb-212	3 4 5	63.3 65 53.3	.78 .60 .43	.865 .643 .358	0.082	2.55	0.0950

Table 1. Activity Size Distribution Data (Track Mine) cont'd. C-2

DATED	Time	Species	D.B. No.	Flowrate ml/s	F_{exp}	F_{theor}	AMD (μm)	GSD	P.I.
Jan. 31	9.10	Pb-214	3 4 5	64.2 62.5 53.3	.695 .49 .129	.744 .435 .178	0.0437	2.471	0.0677
	9.10	Bi-214	3 4 5	64.2 62.5 53.3	.835 .55 .248	.833 .551 .248	0.0605	2.191	0.0018
	9.10	Pb-212	3 4 5	64.2 62.5 53.3	.93 .74 .42	.924 .744 .918	0.10	1.749	0.0060
	9.40	Po-218	3 4 5	61.67 60 48.3	.752 .374 .257	.768 .452 .170	0.0471	2.291	0.0987
Feb. 1	9.40	Pb-214	3 4 5	61.67 60 48.3	.904 .40 .094	.823 .464 .098	0.0475	1.545	0.0881
	9.40	Bi-214	3 4 5	61.67 60 48.3	.902 .481 .127	.849 .519 .116	0.0527	1.454	0.0560
	9.40	Pb-212	3 4 5	61.67 60 48.3	.93 .46 .26	.842 .541 .197	0.0584	1.89	0.1050

TABLE 2. Aerosol Size Distribution Data (Track Mine) C-3
(Flowrate = 60 ml/s)

Dated	Time	Diffusion Batt. No.	F_{exp}	F_{theor}	$\bar{d}$ (μm)	σ_g	P.I.
Jan. 30	9.40	3 4 5	.758 .50 .21	.780 .479 .226	0.0508	2.341	0.0263
	11.40	3 4 5	.774 .581 .129	.845 .522 .171	0.0535	1.52	0.0802
	12.50	3 4 5	.667 .541 .313	.759 .474 .242	0.0502	2.682	0.1037
	13.50	3 4 5	.732 .536 .219	.793 .483 .214	0.0511	2.145	0.0687
Jan. 31	9.35	3 4 5	.809 .553 .298	.819 .548 .291	0.0625	2.422	0.0111
	10.00	3 4 5	.805 .683 .195	.883 .618 .241	0.0651	1.398	0.0880
	11.50	3 4 5	.745 .608 .196	.820 .532 .258	0.0585	2.188	0.0947
	13.00	3 4 5	.805 .634 .171	.856 .564 .238	0.0607	1.723	0.0843
	14.05	3 4 5	.765 .647 .353	.838 .589 .338	0.0717	2.560	0.0793
Feb. 1	10.25	3 4 5	.80 .47 .106	.809 .448 .130	0.0461	1.596	0.0275
	12.20	3 4 5	.865 .46 .127	.814 .479 .172	0.0497	1.759	0.0574
	13.25	3 4 5	.795 .513 .102	.823 .473 .142	0.0485	1.564	0.0487

TABLE 3. Unattached Fractions Calculations (Track Mine) C-4

Dated	Sample Time	Pump Flow-rate L/min	Linear Air Velocity cm/s	E	EC_{ref}	$C_{ref}-C_{WS}$	f_u	Species
Jan. 30	10:50	6.5	27.17	0.52	15.95	1.6	0.10	Po-218
					7.228	2.5	0.35	Pb-214
					3.796	1.36	0.36	Bi-214
					0.708	0.17	0.24	Pb-212
	11:25	6.5	27.17	0.52	12.48	5.4	0.43	Po-218
					6.968	2.35	0.34	Pb-214
					4.056	1.4	0.34	Bi-214
					0.671	0.23	0.34	Pb-212
	13:00	6.5	27.17	0.52	12.22	5.17	0.42	Po-218
					5.689	1.5	0.26	Pb-214
					3.12	1.03	0.33	Bi-214
					0.515	0.05	0.10	Pb-212
Jan. 31	11:00	6.1	25.5	0.54	15.768	1.2	0.08	Po-218
					7.884	0.6	0.08	Pb-214
					4.428	1.2	0.27	Bi-214
					0.648	0.02	0.03	Pb-212
	11:35	6.15	25.71	0.54	18.97	14.74	0.78	Po-218
					9.45	1.0	0.11	Pb-214
					4.97	- 0.86	-0.17	Bi-214
					0.805	0.12	0.15	Pb-212
	13:20	6.2	25.92	0.53	22.737	6.7	0.29	Po-218
					12.667	2.4	0.19	Pb-214
					6.922	1.06	0.15	Bi-214
					0.993	0.24	0.25	Pb-212
Feb. 1	11:30	6.1	25.5	0.54	36.56	- 2.1	-0.06	Po-218
					27.43	5.2	0.19	Pb-214
					22.46	5.2	0.23	Bi-214
					1.75	0.35	0.20	Pb-212
	12:05	6.2	25.92	0.53	37.68	31.5	0.84	Po-218
					28.78	2.2	0.08	Pb-214
					23.37	5.3	0.23	Bi-214
					1.78	0.35	0.20	Pb-212
	13:50	6.1	25.5	0.54	40.5	18.0	0.44	Po-218
					27.81	7.7	0.28	Pb-214
					21.38	2.5	0.12	Bi-214
					1.57	0.41	0.26	Pb-212

TABLE 4: Activity Size Distribution Data (Trackless Mine) C-5

Dated	Time	Species	Diffusion Batt.No.	Flowrate mℓ/s	F_{exp}	F_{theor}	AMD (μm)	GSD	P.I.
Feb. 4	8.40	Po-218	3 4 5	61.67 61.67 56.7	.897 .655 .373	.889 .665 .364	0.0837	2.062	0.0119
	8.40	Pb-214	3 4 5	61.67 61.67 56.7	.945 .766 .366	.921 .737 .393	0.0913	1.479	0.0354
	8.40	Bi-214	3 4 5	61.67 61.67 56.7	.867 .736 .393	.905 .704 .414	0.0958	2.090	0.0425
Feb. 5	8.40	Pb-214	3* 4* 5	54.2 62.5 62.5	.649 .431 .382	.756 .500 .267	0.0533	2.757	0.1345
	8.40	Bi-214	3* 4* 5	54.2 62.5 62.5	.845 .587 .41	.847 .625 .371	0.0784	2.498	0.0457
	8.40	Pb-212	3* 4* 5	54.2 62.5 62.5	.96 .73 .41	.919 .754 .427	0.0916	1.29	0.0423
	* Samples taken 10 minutes later than reference and #5								
Feb. 6	9.00	Po-218	3 4 5	62.5 62.5 55	.852 .56 .305	.836 .576 .292	0.0663	2.398	0.0199
	9.00	Pb-214	3 4 5	62.5 62.5 55	.846 .669 .275	.884 .638 .296	0.0729	1.812	0.0421
	9.00	Bi-214	3 4 5	62.5 62.5 55	.845 .70 .29	.894 .661 .314	0.0769	1.750	0.0536
	9.00	Pb-212	3 4 5	62.5 62.5 55	.87 .69 .40	.892 .679 .386	0.0898	2.231	0.023
	9.15	Po-218	3 4 5	62.5 62.5 55	.927 .641 .236	.898 .661 .240	0.0692	1.294	0.0307
	9.15	Bi-214	3 4 5	62.5 62.5 55	.917 .75 .354	.918 .727 .375	0.0895	1.557	0.0265
	9.15	Pb-212	3 4 5	62.5 62.5 55	.82 .74 .48	.891 .696 .438	0.103	2.677	0.075

TABLE 4 : Activity Size Distribution Data (Trackless Mine) cont'd.

Dated	Time	Species	Diffusion Batt No.	Flowrate ml/s	F_{exp}	F_{theor}	AMD (μm)	GSD	P.I.
Feb. 7	9.10	RnWL	3 4 5	48.3 60 48.3	.892 .730 .378	.901 .722 .382	0.0975	1.839	0.0104
	9.40	RnWL	3 4 5	48.3 60 53.3	.862 .698 .341	.883 .680 .352	0.0853	1.86	0.0241
	10.10	RnWL	3 4 5	48.3 60 48.3	.80 .697 .352	.854 .652 .363	0.0886	2.55	0.0597
	10.40	RnWL	3 4 5	46.7 58.3 50	.87 .74 .37	.899 .717 .385	0.0963	1.806	0.0320
	8.40	Pb-212	3 4 5	61.7 60 54.2	.968 .83 .489	.941 .799 .517	0.1255	1.681	0.0379
	13.15	Pb-212	3 4 5	58.3 58.3 43.3	.935 .804 .351	.927 .757 .391	0.1066	1.648	0.0518
	13.40	Pb-212	3 4 5	58.3 56.7 45.0	.994 .803 .345	.927 .753 .397	0.1056	1.622	0.0760
Feb. 8	8.45	RnWL	3 4 5	58.3 61.7 58.3	.881 .687 .325	.896 .674 .334	0.0787	1.655	0.0169
	9.15	RnWL	3 4 5	61.7 65 58.3	.918 .772 .352	.916 .730 .389	0.0891	1.578	0.0469

TABLE 5: Aerosol Size Distribution Data (Trackless Mine) C-7

(Flowrate = 60 mL/s)

Dated	Time	Diffusion Batt. No.	F_{exp}	F_{theor}	$\bar{d}$ (μm)	σ_g	P.I.
Feb. 4	9.30	3 4 5	.89 .71 .38	.904 .693 .394	0.0884	1.837	0.0201
	12.40	3 4 5	.95 .78 .39	.923 .743 .422	0.0938	1.435	0.0430
Feb. 5	9.20	3 4 5	.885 .846 .115	.900 .669 .270	0.0705	1.150	0.1989
	11.50	3 4 5	.923 .846 .246	.911 .705 .368	0.0839	1.485	0.1574
	12.50	3 4 5	.622 .35 .119	.646 .326 .129	0.0321	2.505	0.0286
Feb. 6	9.45	3 4 5	.836 .616 .205	.869 .585 .231	0.0619	1.547	0.0403
	12.00	3 4 5	.846 .385 .231	.784 .450 .175	0.0468	1.976	0.0808
	13.05	3 4 5	.84 .763 .244	.903 .677 .317	0.0760	1.409	0.0995
Feb. 8	10.05	3 4 5	.818 .727 .20	.889 .637 .280	0.0697	1.503	0.1072
	10.20	3 4 5	.858 .75 .183	.893 .648 .281	0.0704	1.427	0.1195

TABLE 6. Unattached Fractions Calculations (Trackless Mine)

Dated	Sample Time	Pump Flowrate L/min	Linear Air Velocity cm/s	E	EC_{ref}	$C_{ref} - C_{WS}$	f_u	Species
Feb. 4	10:45	6	25.08	0.54	35.75 20.68 13.66 1.188	9.2 2.7 0.3 0.1	0.26 0.13 0.02 0.08	Po-218 Pb-214 Bi-214 Pb-212
	11:20	6	25.08	0.54	33.2 20.57 13.82 1.296	4.2 2.2 2.4 0.2	0.13 0.11 0.17 0.15	Po-218 Pb-214 Bi-214 Pb-212
	13:00	5.9	24.66	0.55	31.51 20.95 14.46 1.21	9.7 5.1 4.85 0.35	0.31 0.24 0.33 0.29	Po-218 Pb-214 Bi-214 Pb-212
Feb. 5	10:40	3.7	15.5	0.68	32.3 19.42 13.10 1.136	- 0.6 2.1 3.11 0.13	-0.02 0.11 0.24 0.11	Po-218 Pb-214 Bi-214 Pb-212
	11:15	3.7	15.5	0.68	37.33 18.97 11.36 1.129	- 0.6 0.8 1.11 - 0.02	-0.02 0.04 0.10 -0.02	Po-218 Pb-214 Bi-214 Pb-212
	13:05	3.6	15.05	0.69	43.263 21.266 12.61 1.18	13.2 2.62 - 0.34 0.09	0.30 0.12 -0.03 0.08	Po-218 Pb-214 Bi-214 Pb-212
Feb. 6	11:05	6.2	25.92	0.53	32.648 18.02 12.19 0.88	17.8 4.0 2.0 0.22	0.54 0.22 0.16 0.25	Po-218 Pb-214 Bi-214 Pb-212
	11:40	6	25.08	0.54	27.54 17.6 12.74 0.821	- 1.7 2.8 2.4 0.02	-0.06 0.16 0.19 0.02	Po-218 Pb-214 Bi-214 Pb-212
	13:25	6	25.08	0.54	31.05 17.5 12.58 1.01	15.0 0.5 0.9 0.14	0.48 0.03 0.07 0.14	Po-218 Pb-214 Bi-214 Pb-212

TABLE 6: Unattached Fraction Calculations (Trackless Mine) cont'd.

Dated	Sample Time	Pump Flowrate (L/min)	Linear Air Velocity (cm/s)	E	EC_{ref}	$C_{ref}-C_{WS}$	f_u	Species
Feb. 7	9:20	5.6	23.41	0.56	0.2	0.013	0.06	RnWL
	9:50	5.5	23	0.57	0.17	0.016	0.09	RnWL
	10:20	5.4	22.57	0.57	0.185	0.049	0.26	RnWL
	10:55	5.6	23.41	0.56	0.193	0.031	0.16	RnWL
	8:55	5.6	23.41	0.56	1.07	0.07	0.06	Pb-212
	12:25	5.7	23.83	0.56	0.97	0.05	0.05	Pb-212
	12:45	6	25.08	0.54	0.94	0.21	0.22	Pb-212
	14:00	5.7	23.83	0.56	0.952	0.05	0.05	Pb-212
Feb. 8	8:55	6.2	25.92	0.53	0.159	0.038	0.24	RnWL
	9:25	6.5	27.17	0.52	0.144	0.015	0.10	RnWL
	9:55	6.8	28.4	0.51	0.175	0.026	0.15	RnWL
	8:25	6	25.08	0.54	0.945	0.11	0.12	Pb-212
	12:00	6.5	27.17	0.52	0.863	0.19	0.22	Pb-212
	12:20	5.6	23.41	0.56	0.913	0.19	0.21	Pb-212
	13:35	4.7	19.65	0.61	1.0	0.12	0.12	Pb-212

APPENDIX D

Glossary of Terms

Aerosol	- A stable suspension of solid or liquid particles in a gas.
Coagulation	- The joining of particles to each other through collision.
Electrical Mobility	- The ratio of particle terminal velocity to the applied electrical force, assuming one electric charge on the particle.
Aerodynamic Diameter	- The diameter of a unit density sphere that would have the same terminal velocity due to gravity as the particle under consideration.
Log-normal Distribution	- A distribution in which the logarithm of the variable is normally distributed.
Geometric Standard Deviation	- The measure of dispersion for a log-normal distribution; the ratio of the 84.13 percentile to the 50 percentile.
Geometric Mean	- The measure of central tendency for a log-normal distribution; the 50th percentile.
Particle Size Distribution	- The frequency of occurrence of particles of various sizes in a sample.
Median	- The 50th percentile demarkation for a distribution.
Count Median Diameter	- The diameter corresponding to the 50th percentile of the distribution in number of particles versus aerodynamic diameter.
Activity Median Diameter	- The diameter corresponding to the 50th percentile of the distribution in surface area of the aerosol particles versus aerodynamic diameter.
Volume Median Diameter	- The diameter corresponding to the 50th percentile of the distribution in volume of the aerosol particles versus aerodynamic diameter.